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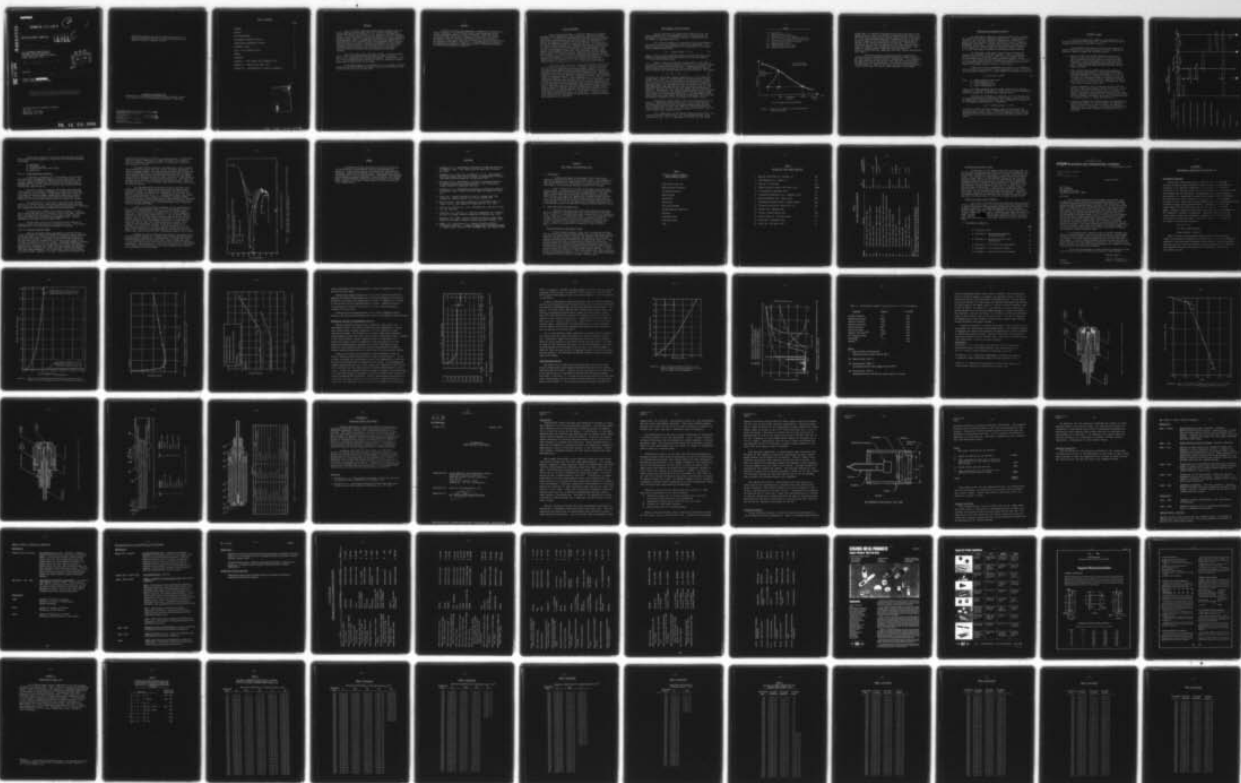UNCLASSIFIED   EXXON/GRUS. 1BFB-78   AFOSR-TR-78-1508   NL
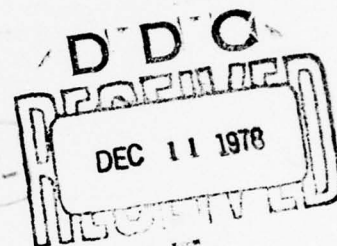
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RADIATION AUGMENTED COMBUSTION

LEVEL II

A. E. CERKANOWICZ AND W. BARTOK
GOVERNMENT RESEARCH LABORATORIES
EXXON RESEARCH AND ENGINEERING COMPANY
LINDEN, NEW JERSEY 07036

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FOREWORD

This is an annual report on research studies conducted with the partial support of the Air Force Office of Scientific Research under Contract No. F49620-77-C-0085 with Dr. B.T. Wolfson as the AFOSR project monitor. Exxon furnished scientific effort together with all the necessary related services, facilities, supplies and materials to conduct theoretical and experimental studies to demonstrate and characterize augmentation of combustion initiation, reaction kinetics and propagation rate in pratical fuel-air mixtures at reaction conditions encountered in aircraft engine combustors and after-burners. The necessary funds for the acquisition of suitable vacuum ultraviolet and ultraviolet light sources were proved by the Air Force Aero Propulsion Laboratory via the AFOSR contract.

This first annual report represents progress of research through May 31, 1978 at Exxon Research and Engineering, Linden, New Jersey with Dr. A.E. Cerkanowicz as principal investigator. The work was carried out in the Government Research Laboratories Division, Combustion Science Group under the direction of Dr. W. Bartok.

As an annual report, this documentation is not intended to provide extensive detail but to primarily document the status and direction of the scientific research effort at this time.

ABSTRACT

Radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediary species is being investigated. Pulsed VUV (vacuum ultraviolet) light sources and continuous UV (ultraviolet) light sources are being used for this purpose. Experimental efforts are directed at elucidation of light source conversion efficiency and spectral characteristics, and reactant mixture-photon interactions. A complimentary effort involves the development of analytical capability required for modeling photochemical initiation and enhancement of combustion.

OBJECTIVE/APPROACH

Present aircraft operation is limited by combustion associated phenomena such as flammability, flame propagation, ignition and stable combustion. An insufficient understanding is available of basic mechanisms and processes associated with promising techniques for enhancement of combustion and combustion initiation and for evaluation of feasibility of concepts for extending operability range and stability. The objective of the subject research program is to investigate and evaluate the feasibility of various techniques for extending current aircraft operational limitations which are encountered due to combustion associated phenomena, with emphasis on photochemical techniques. And to formulate realistic mathematical models describing the ignition, combustion and stability enhancement phenomena. This work will provide additional understanding and modeling of these processes. It will aid in evaluating the potentials of various techniques, including photochemical energy addition, for providing efficient means of extending aircraft operational range beyond the continuous flight corridor presently dictated by normal (spark) ignition.

The overall program approach encompasses experimental and analytical assessment of promising techniques for extending aircraft operational limitations due to combustion associated phenomena. Emphasis will be on the study of photochemical radiative augmentation techniques to enhance combustion initiation, reaction kinetics and propagation rate. Particular attention will be given to combustion aspects which represent limiting conditions on combustor operation such as flammability limits, flame propagation, ignition and stability limits. Other approaches such as use of laser irradiation, modified spark and plasma-torch will also be considered. Suitable vacuum ultraviolet and ultraviolet sources are being acquired and will be fully characterized using spectroscopic and combustion diagnostic techniques. Additional tests will delineate photon-reactant mixture interaction. Characterization of enhanced ignition and combustion by photochemical and other techniques at aircraft combustor and afterburner conditions will be explored in a flow combustor both in a simple premixed mode and in a cannular combustion mode using gaseous and liquid fuels. Consistent experimental and theoretical descriptions of the ignition and combustion enhancement phenomena will be developed.

PHOTOCHEMICAL IGNITION PRINCIPLE

Based on qualitative and quantitative analysis of, and sub-
sequent agreement with, the experimental results, a mechanism for the
photochemical initiation of sustained combustion in unsensitized fuel-
air systems has been developed (1-4).

The initiation mechanism is considered to follow a photochemical
path wherein the critical intermediary species are oxygen atoms. The
atoms are generated by photodissociation of oxygen molecules via radiant
energy absorption below 245 nm.

$$O_2 + \text{radiant energy} \rightarrow O + O \qquad (1)$$
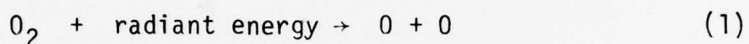
However, the most efficient photodissociative production of atoms occurs
primarily at wavelengths below 180 nm where one of the atoms produced
is in an excited electronic state.

When a critical concentration of oxygen atoms, on the order of
10^{14} atoms/cm^3, is achieved or exceeded at any point in the reactant mixture
combustion initiation (not ignition) occurs. Subsequent reaction of the
atomic oxygen with fuel molecules (as well as other combustion species)
leads to ignition and sustained combustion via chain reactions. For example,

$$O + RH \rightarrow OH + R \qquad (2)$$
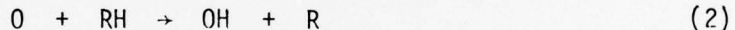
Illustrated on a phase plane diagram (temperature vs. log of oxygen atom
concentration - Figure 1), the photochemical initiation process follows
path NP. At point P, the critical oxygen atom concentration is achieved
and the mixture crosses the separating line CC into the self-sustaining
combustion region. The subsequent reactions are different from the usual
high temperature oxygen atom reactions since the process starts at a low
temperature (point P) and not at the usual thermal ignition temperature
(point T). Additionally, since radiant absorption below 180 nm is primarily
responsible for initiation, the presence of electronically excited oxygen
atoms further alters and enhances the kinetics. The experimental results
indicate that the radiant energy consumed for photochemical ignition by the
photochemical technique is only on the order of 0.1μJ/nm at 150 nm.

Absorption of radiant energy by the fuel is postulated to be un-
necessary. Qualitative verification of this is found in the fact that
hydrogen-oxygen-nitrogen mixtures and methane-oxygen-nitrogen mixtures
can be ignited photochemically using sapphire as the window material for
radiant transmission. In these cases, the only radiative process which can
occur involves oxygen photodissociation.

For a radiant pulse at the threshold energy initiation level, the
initiation time (not ignition time) will be approximately equal to the
radiant pulse time. This is a consequence of the fact that the radiant

- 3 -

N: nodal point
T: thermal ignition point
P: photochemical ignition point
E: lower limit point for enhanced combustion
C-C: separating line between non-combusting and
self-sustained combustion regions
N-T: thermal ignition path
N-P: photochemical ignition path
E-P: enhanced combustion region
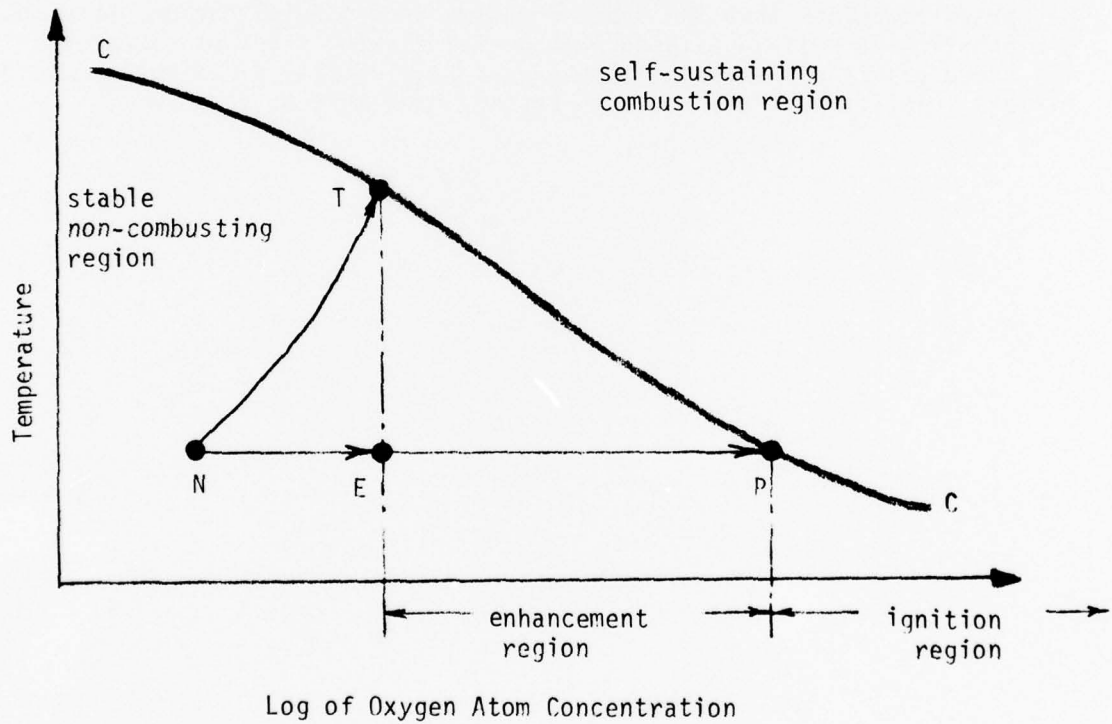
Figure 1. Phase Plane Diagram for a Chain-Branching Combusting System

energy input is essentially integrated over the time of the pulse by the reactant mixture. During this period, the absorbed radiant input is insufficient to cause any excessive heating effects and thus the initiation will occur under isothermal conditions. Additionally, only a small percentage of molecules are dissociated during the initiation period and thus the initial species concentrations are constant. Combining this information with the ideal gas equation of state shows that the pressure within the chamber is also constant during the initiation phase. Consequently, the photochemical combustion initiation mechanism occurs at constant pressure, temperature and initial species concentration (see Figure 1).

The underlying physical phenomena involved in modeling the initiation process are photo-absorption--followed by photodissociation, gas phase reactions, diffusion and wall recombination. It is through the gas phase reactions that the process passes from the initiation phase to the ignition or self-sustaining phase. For flowing reactant mixtures, the added effect of "smearing" the oxygen atom density distribution due to mixture velocity past the radiant source window must be considered.

PHOTOCHEMICAL ENHANCEMENT PRINCIPLE

The photochemical combustion enhancement mechanism also involves the production of critical intermediary species (1-4). Oxygen atom concentrations less than that required for photochemical initiation but greater than that achieved in thermal ignition will result in combustion enhancement (see Figure 1). Following the production of oxygen atom concentrations in this range, ignition can then be achieved by increasing mixture temperature to levels below that needed for thermal ignition. As a result, less energy is expended in the enhanced ignition process.

The enhancement region spans several decades of oxygen atom concentration (typically 10^7 to 10^{14} atoms/cm^3). Due to the lower concentration levels, the enhancement effect can occur at greater depths into the mixture and can utilize higher wavelength radiation. In the 0 to 0.3 m region (measured from the radiant source window into the mixture) the wavelength range of interest is 165 to 185 nm while in the 0.3 to 3 m region the wavelength range of interest is 175 to 245 nm.

Lowering of ignition requirements also results in an increase in iginition kernal growth rate and in flame propagation velocity. This effect can be described by appealing to a simple thermal flame propagation theory (5);

$$V \sim [(T_f - T_i)/(T_i - T_o)]^{1/2} \tag{3}$$

where V = flame propagation speed (m/s)
       T_f = flame temperature (K)
       T_i = ignition temperature (K)
       T_o = initial temperature (K)

Clearly, the flame propagation velocity should increase as the ignition temperature is lowered. Measurements of flame travel following photochemical iginition indicate that increased flame speed does occur.

Photochemical enhancement of combustion can also be brought about by irradiating a combusting, hydrocarbon fueled mixture. Norrish et.al (6) has demonstrated increased reaction rates due to photochemical dissociation of the degenerate-branching-species formaldehyde:

$$H_2CO + \text{radiant energy} \rightarrow H + HCO \tag{4}$$
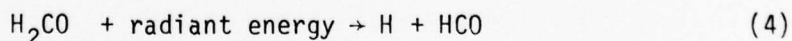
This reaction allows the slow, degenerate steps to be by-passed, thus enhancing overall reaction rate. Formaldehyde absorption occurs over the wavelength range of 250 to 360 nm (7) and in comparison with oxygen photodissociation utilizes the normally more intense radiation region of light sources.

STATEMENT OF WORK

The current program work statement is presented below for the effort covering the period June 1977 - December 1978 and a revised program milestone chart is provided in Figure 2:

The contractor shall furnish scientific effort during the period, together with all related services, facilities, supplies and materials, needed to conduct the following research:

a. Identify, acquire and evaluate appropriate vacuum ultra-violet and ultraviolet light sources. Purchase of avail-able and specially modified sources will be pursued under subcontract. Source requirements will be specified based on previously determined photochemical combustion require-ments. (AFOSR contract F44620-70-C-0051 and AFAPL contract F33615-73-C-2063).

b. Select and characterize radiant sources for program use. Spectrographic measurements will be employed to determine wavelength dependence of source energy output as a function of energy input and pulse duration. Pulsed sources will be evaluated in the 145-185 nm range and continuous source will be evaluated in the 200-360 nm range. Combustion initiation tests using static mixtures will also be performed to further characterize the source radiant beam.

c. Initiate experimental tests to identify and investigate the details of radiant beam-reactant mixture interaction. Explore the effects of inerts, fuel-free air zones, and depth of radiation penetration on the photo-combustion processes using gaseous, stationary reactant mixtures. Also design and initiate plug flow combustor experiments to provide for characterization of radiative effects in flowing reactive mixtures.

d. Carry out a comprehensive technical analysis to complement the experimental program. The detailed aspects of radiation-com-bustion interaction which lead to ignition and combustion enhancement will be considered. A consistent experimental and theoretical description of combustion augmentation will be developed.

FIGURE 2

PROGRAM MILESTONE REVISED (6/1/78)

A - Status as of June, 1978

B - Projected Status, December, 1978
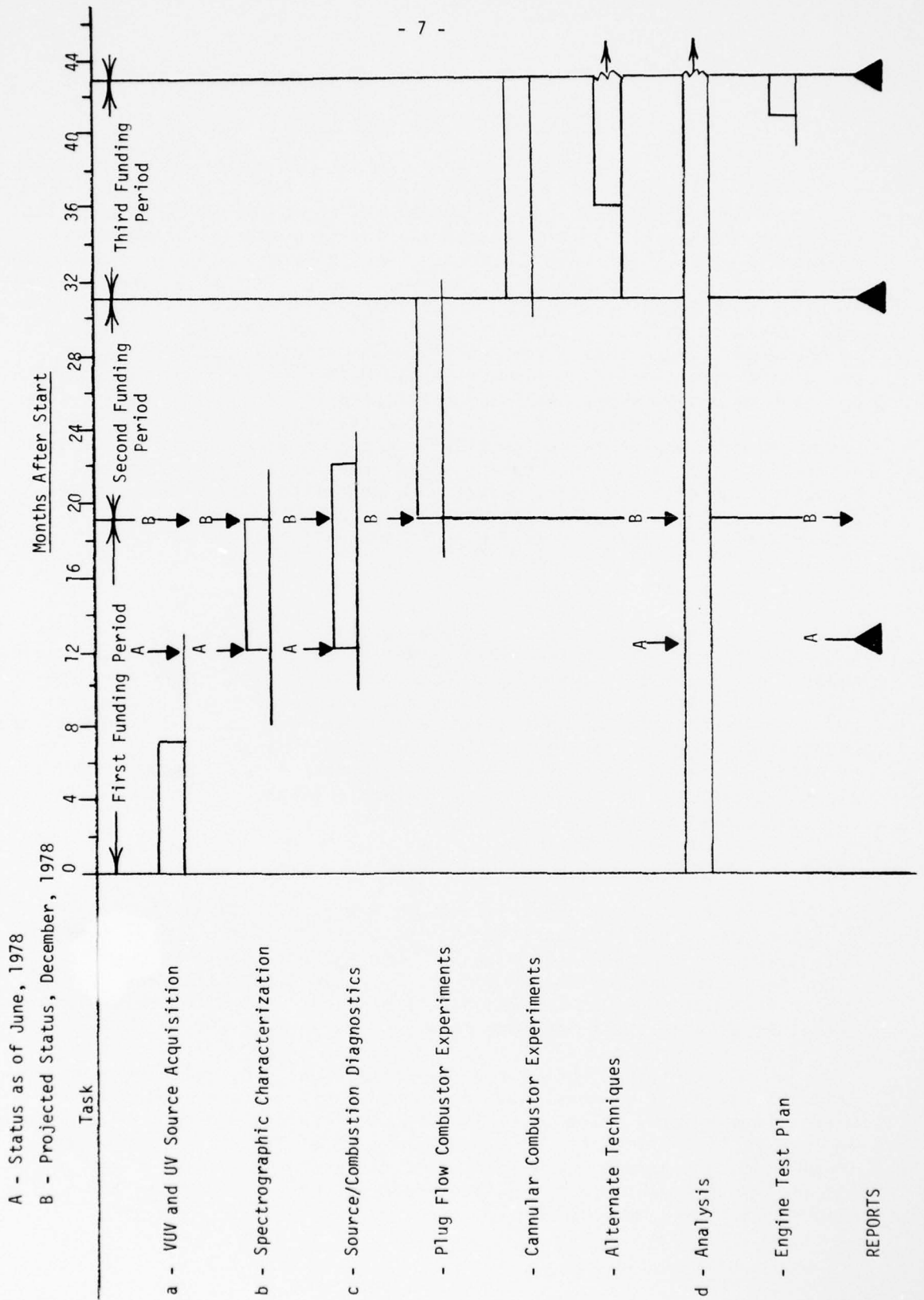
STATUS OF THE RESEARCH EFFORT

During the past year, progress has been made on the evaluation, selection, acquisition, and characterization of suitable vacuum ultraviolet and ultraviolet light sources. Spectrographic and combustion diagnostic tests are being set-up to determine radiant output intensity as a function of spectral wavelength, input energy, time, and distance from the light source. Radiative ignition requirements of standard mixtures will be measured. These measurements are scheduled to be completed by the end of the first period. A comprehensive mathematical model of radiative ignition of hydrogen-oxygen-nitrogen mixtures is being formulated. The model includes the effect of light source characteristics; photo-dissociation of light absorbing species; reactant mixture kinetics, including electronically excited state species; species diffusion and wall recombination effects. This advanced computerized, model has provided a consistent description of the spatial and time behavior of species concentration and temperature for photochemically initiated combustion.

(Task a) Light Source Selection

Fourteen light source manufacturing specialists were contacted and their capabilities evaluated with regard to the specified light source needs. As a result of this evaluation, the three light source systems outlined in Table 1 were selected and acquired for use in the program. The VUV source required some development effort and was based on improved versions of the previous designs utilized for photochemical ignition. The UV and combined VUV/UV sources were selected essentially from product lines after a thorough screening process. Appendix I provides further details on light source selection and acquisition.

(Task b) Spectrographic Characterization

A McPherson Model 216.5 vacuum ultraviolet (VUV) spectrograph is being set-up for the characterization of light source spectral output. This system is evacuable to about 10^{-6} kPa and utilizes a magnesium fluorite coated grating blazed for 150 nm. Light detection in the VUV region is provided by an EMR Photoelectric Model 541N-09-14 multiplier phototube with spectral response to 135 nm.

The primary light source measurement will be relative spectral intensity over a 1 nm wavelength region per unit area of light source window ($J/s \cdot nm \cdot cm^2$). The spectral range of interest for each of the three sources is listed in Table 1. A Tektronics Model 555 oscilloscope with Polaroid camera attachment will be used to record the pulsed light source output intensity while a strip-chart recorder will be used for the continuous light source measurements.

TABLE 1

RADIATIVE AUGMENTED COMBUSTION
PROGRAM LIGHT SOURCE SYSTEMS

Source	1-VUV	2-UV	3-VUV/UV
Spectral Range	140-200 nm	200-400 nm	150-400 nm
Window	UV Grade Sapphire	High Grade Quartz	Normal Sapphire
Optics	Point Source with No Collecting Optics	Focused by Elliptical Reflector - Lens Assembly for Parallel Beam	Focused - Elliptical Reflector Sealed in Arc Chamber
Optical Path	Zero, Evacuated	Air	Zero, Evacuated, Air
Mode	Pulsed, $\tau < 10^{-4}$ s	Continuous	Continuous
Energy/Power Input	0.5 to 50 J	0 to 1 kW	0 to 500 W
Plasma Source	Xenon Short Arc	Mercury-Xenon Short Arc	Xenon Short Arc
Approx. Pressure	300 kPa	300 kPa	300 kPa
Combustor Function	Ignition	Enhancement	Aspects of Ignition/Enhancement
Supplier	ILC	ORC	EIMAC

Pulsed and/or continuous light source intensity and pulse shape (where appropriate) measurements as a function of the following parameters are planned:

- wavelength
- energy/power input
- distance from light source window
- window area

(Task c) Source/Combustion Diagnostics

A stationary, combustion cell 2.5 cm diameter by 30 cm long is being fabricated for combustion diagnostics of the light sources. The cell will contain subatmospheric reactant mixtures comprised of either hydrogen, methane or propane fuels and oxygen or air as the oxidant. A photodetector array will be utilized to record flame propagation speeds following the ignition process.

Provision is made for combustion initiation using either VUV light sources or in-situ spark discharges, or a combination of both VUV or UV light and spark discharge. An adjustable length cell will be utilized between the reactant chamber window and the light source (double window system). The intervening space between the two windows can be evacuated or filled to various pressures with air, oxygen, or nitrogen.

The combustion cell will be used to characterize the ignition capability of the VUV sources. When used in conjunction with the adjustable length cell, the influence of beam spreading and absorption or scattering due to penetrating fuel-free gas volumes will be characterized.

The VUV/UV source (EIMAC) will be used in attempts to directly ignite reactant mixtures with a continuous, focused light beam. Subsequent tests will investigate the influence of this source on spark ignition energy requirements and subsequent flame propagation rates. Similar measurements are planned for the UV source (ORC).

The VUV source (ILC) will be utilized for direct ignition of reactant mixtures with and without the intervening air cell. The principle measurement will be the pulse energy requirement for ignition.

(Task d) Radiative Initiation Model

Physical and chemical events considered in the model include: radiant absorption by reactant and combustion-intermediate species according to the Beer-Lambert Law, chemical reactions including photo-dissociation and excited state kinetics. Diffusion of species along the direction of the light beam, and wall recombination at the light source window will be included in subsequent versions of the model. Wavelength dependent absorption cross-sections for O_2, O_3, H_2O, HO_2 and H_2O_2 are utilized. Light source characteristics considered by the model are window transmission (wavelength dependent), beam spreading angle, pulse time, and intensity (wavelength, time, input energy dependent). The current model is specifically limited to H_2-O_2-N_2 systems. Appendix II presents a tabulation of the kinetic and

adsorption characteristics included in the computer model. In computations
where the reactant temperature is allowed to increase, each element of
the gas is treated as an adiabatic system. No convective or conductive
heat transport is allowed.

The model involves solution of one-dimensional, partial differen-
tial equations which govern individual species and energy conservation. A
number of computer programs have been obtained, modified, and installed for
use in the modeling effort. A versatile equation-writer code has been re-
ceived from Los Alamos Scientific Laboratory which generates the FORTRAN
code required to describe the chemical kinetic effects of a large number of
reactions on the individual species balance equations.(8) The program also
produces code to calculate the Jacobian of the equation system. Input to
the equation-writer is a set of reaction cards listing reactants and products,
one card per reaction.

The code generated by the equation-writer is being used with a
stiffly stable multistep method of Gear for solving the equations when
diffusion of species is neglected.(9) Subroutines have been written or
modified to evaluate the chemical and photochemical rate constants and to
model the photo-absorption of O_2 in the Schumann-Runge bands. For solving
the system when diffusion of species is considered, a program, PDECOL,
(written at Lawrence Livermore Laboratory) has been obtained which numerically
solves coupled systems of non-linear partial differential equations in one
space and one time dimension.(10) The equation-writer code is being mod-
ified to interface with PDECOL.

Figure 3 illustrates model predictions for the irradiation of a
298 K, 40 kPa, hydrogen-oxygen mixture. Each curve represents a photo-
chemical path (time implicit) in the phase plane for a given radiant
intensity. The radiant pulse was assumed to be a critically damped dis-
charge with a time to peak intensity of 20 µs. For low radiant intensi-
ties (50, 75, 80) the radiant pulse generates oxygen atoms and some tem-
perature rise, but the final tendency of the mixture is to return to the
initial conditions that existed before irradiation. At higher radiant
intensities (85, 90, 100), the irradiated mixture has entered the un-
stable zone and the tendency to return to the initial conditions is
overcome. All of these high intensity conditions eventually result in
rapid burning (combustion). Care must, however, be exercised in using
these results since the current program does not include heat loss and the
kinetic rates used are valid only over a temperature range of 298 to 1500 K.

Although the results indicated are preliminary, qualitatively the
predicted behavior compares very favorably with previous description based
on general phase plane analysis. Quantitatively, the oxygen atom concen-
tration achieved during the initiation phase (time less than about 100 µs)
is about 80-85 times greater than estimated previously based on experimental
measurements. Detailed results on light source characteristics, and explorat-
ion of kinetic and absorption data in the current program should provide
for rectification of this difference.
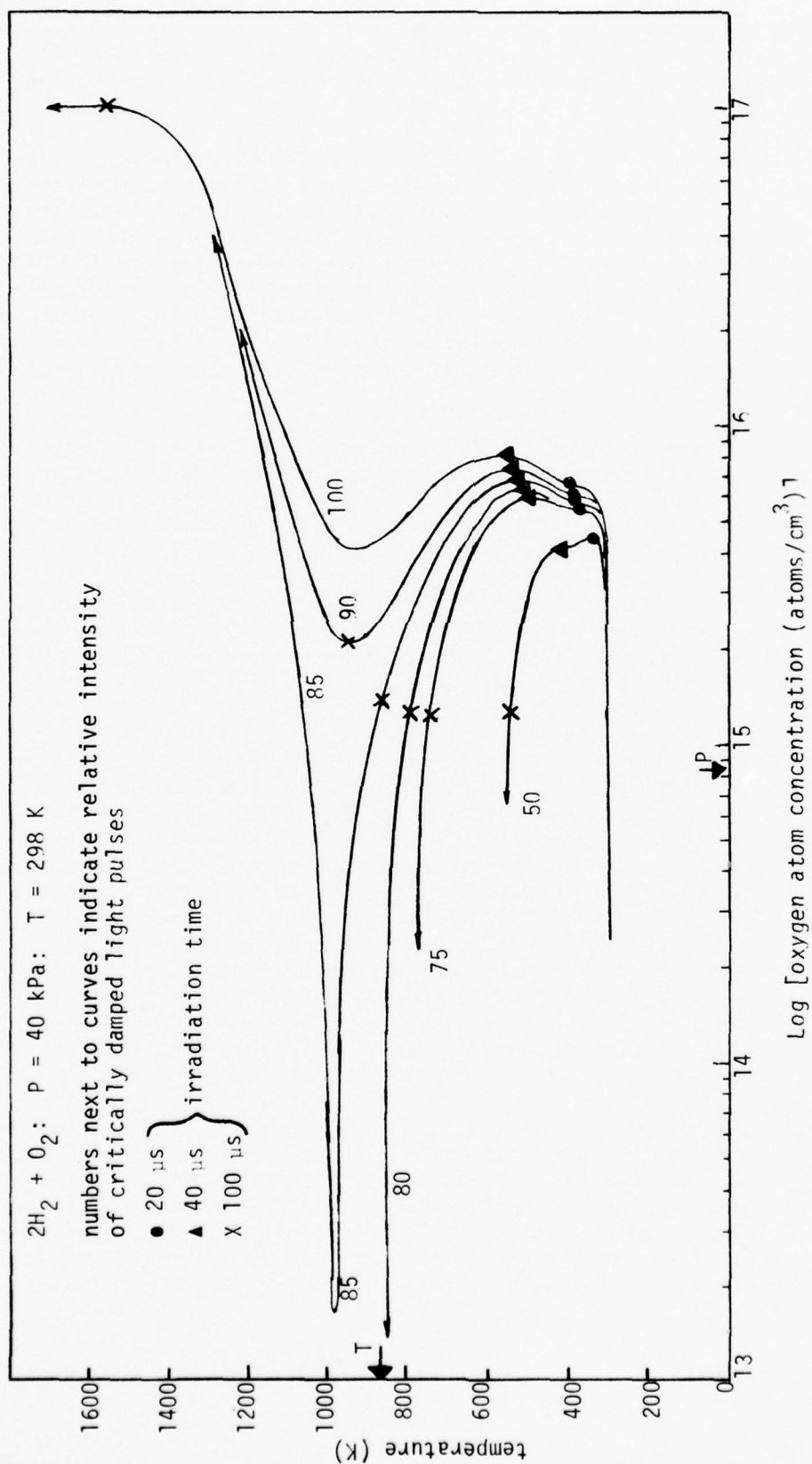
Figure 3. Phase plane paths for a stoichiometric hydrogen-oxygen mixture irradiated with various VUV pulsed light intensities.

SUMMARY

Experimental direction and analytical results are described for the exploration of photochemical ignition and enhancement of combustion. Light source evaluation and selection has been completed. Continuous, focusable, UV and VUV/UV sources have been acquired, but the pulsed VUV source is still being fabricated. Experimental spectrographic and photochemical combustion equipment is being assembled, and a computer model of the photochemical combustion initiation process is being formulated. Appendix III documents presentations of and interest expressed in the program effort.

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APPENDIX I

LIGHT SOURCE SELECTION ACQUISITION

A. Introduction

A planned requirement of the program is the identification, selection, and acquisition of specialized light sources. These sources provide for the generation of intense photon flux in the vacuum ultraviolet (VUV) region from 140 nm to 200 nm and in the ultraviolet (UV) region from 200 to 400 nm. Both pulsed and continuous sources are of interest.

Table 1 presents a list of the various types of VUV and UV generating sources. The high pressure short arc and medium pressure discharge lamps currently represent the most practical VUV/UV devices. The other sources listed suffer from low intensity (glow discharge), uncontrolled chemical effects (microwave) and window material damage problems (ablation arc). Gas discharge lamps with additives may provide for more efficient systems in the future but are currently limited to higher wavelength regions or low intensity. Lasers are not commercially available below 193 nm but could eventually prove to be important alternate (although expensive) sources.

B. Light Source Selection/Acquisition

Fourteen light source manufacturing specialists were contacted, and their capabilities evaluated with regard to the specified light source needs. Table 2 lists potential light source suppliers and a brief evaluation of their capabilities is presented in Table 3. The selection and evaluation of these light source suppliers was based on assessment of available literature, phone contact, and written solicitation of additional information. Attachments to this appendix are provided which document the typical written correspondence with the suppliers listed in Tables 2 and 3.

Vacuum Ultraviolet Light Source (1-VUV)

Of the fourteen companies listed, only ILC Technology and EIMAC have the technology of brazed sapphire window seals and high pressure pulsed xenon short arc design which is essential for acceptable VUV source operation. The other suppliers have weaker resonance type sources or employ quartz windows which preclude the attainment of the required VUV light flux. EIMAC initially expressed interest in providing the required source when the program proposal was being prepared and verbally indicated their effort at $50,000 and one year. However, subsequent conversation with EIMAC indicated that they have no interest in pursuing a program of this nature. ILC Technology had expressed interest in providing the required VUV source. A visit to their facilities on October 17, 1977, indicated that they have the necessary personnel, equipment and experience for this purpose. Their effort (described in Attachments D and E) involves a $21,000, six-month effort.

TABLE 1

POTENTIAL VACUUM ULTRAVIOLET
AND ULTRAVIOLET SOURCES

High Pressure Short Arc

Medium Pressure Discharge

Low Pressure Long Arc

Glow Discharge

Vacuum Spark

Ablation Arc

Capillary Discharge

Gas Discharge with Additives

Microwave

Induction Plasma

Black Body Source

Laser

TABLE 2

SPECIALIZED LIGHT SOURCE SUPPLIERS

1.	American Ultraviolet Co., Chatham, N.J.	AUC
2.	Conrad-Hanovia Inc., Newark, N.J.	CHI
3.	EG&G Inc., Salem, Mass.	EGG
4.	EIMAC Division of Varian, San Carlos, Calif.	EIMAC
5.	ILC Technology, Sunnyvale, Calif.	ILC
6.	Illumination Industries, Inc., Sunnyvale, Calif.	III
7.	Optical Radiation Corp., Azusa, Calif.	ORC
8.	Photochemical Research Assoc., London, Ontario	PRA
9.	Scientific Services Co., Rocky Hill, N.J.	SSC
10.	Tachisto Inc., Needham, Mass.	TT
11.	TRW Inc., Redanco Beach, Calif.	TRW
12.	Voltaic Tubes Inc., Fairfield, Conn.	VTI
13.	Xenon Corp., Wilmington, Mass.	XC
14.	Xonics Inc., Van Nuys, Calif.	XI

TABLE 3

LIGHT SOURCE TYPES AND VUV GENERATION

Company	Comments	VUV Capability	VUV Intensity photons/cm$^2 \cdot$s (1)
AUC	long arc systems, quartz optics, USHIO lamps	No	--
CHI	Xe and Hg-Xe short arcs, quartz optics, no systems	No	--
EGG	flash tubes, strobe lights	Modification	2.7×10^{15}
EIMAC	continuous Xe short arc, sapphire optics, focused	Yes	continuous, focused(2)
ILC	flash lamps, short arcs, sapphire braze capability	Yes	1×10^{17} (3)
III	capillary lamps, short arcs, long arcs, quartz optics, no systems	No	--
ORC	Xe and Hg-Xe short arc systems, commercial projection business	No	--
PRA	Xe and Hg-Xe short arc systems, purchase lamps	Developing	--
SSC	low pressure resonance lamps, continuous	Yes	2×10^{15}
TI	XeF excimer laser at 193 nm	Yes	insufficient
TRW	ablation arc, windowless, company out of business	Modification	3×10^{17}
VTI	flash tubes, USHIO lamps	No	--
XC	primarily flash tubes, quartz optics	Modification	1×10^{16}
XI	resonance lamp for calibration purposes	Yes	8×10^{12}

NOTES:
(1) Continuous sources evaluated for 10^{-4}s irradiation time.
(2) Insufficient information to assess focused VUV intensity.
(3) Will fabricate light source as per previous photochemical igniter designs.

Ultraviolet Light Source (2-UV)

Although many of the companies identified can provide short arc mercury-xenon or xenon continuous light sources with quartz envelopes, only two companies responded with the capability to provide a complete optical system. This includes lamp, lamp housing, optical lenses and reflectors, cooling and power supply. Optical Radiation Corporation not only markets complete systems, but has the facility for manufacturing all components. Photochemical Research Associates would provide a system assembled from components partially supplied by other manufacturers. Meetings held with both companies indicated comparable total cost for the basic lamp, lamp house and power supply package. The ORC unit has an apparent edge in efficiency (70% vs. 60%), does not require water cooling and utilizes a power supply that has accumulated more operation hours and is therefore more proven. Acquisition of the ORC system was undertaken. Total price including modifications for converting from a focused to a parallel light beam and for utilizing either a vertical or horizontal beam was $6,075.

Transitional Light Source (3-VUV/UV)

This source is selected to provide capabilities which have aspects of both a VUV and a UV source. For this reason it provides the potential of meeting both ignition and enhancement requirements and provides a useful diagnostic capability. A sapphire windowed device with a continuous, focused output is desirable. The only supplier of a light source of this nature is EIMAC Division of Varian. Illuminator model number VIX-501UV is a sapphire window. ѕ ated elliptical reflector unit with a price of $770. Housing, fan and cable (R500-4) cost $450. Operating power will be provided by the same power supply used for item 2-UV listed above.

C. Attachments to Appendix I

Transmittal Letter

EX🞬ON RESEARCH AND ENGINEERING COMPANY

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GOVERNMENT RESEARCH LABORATORIES
A. SKOPP
Director
Advanced Energy Systems Laboratory

August 18, 1977

Mr. J. Shaw
ILC Technology
164 Commercial Street
Sunnyvale, California 94086

Dear Jim:

As I outlined during our recent telephone conversation, Exxon has embarked on an Air Force sponsored experimental program to evaluate combustion augmentation by means of ultraviolet light irradiation. This program is based on past work which I carried out for the Air Force (Final Report Nos. AFOSR-TR-74-0153 and AFAPL-TR-74-87) as summarized in Attachment A. I believe that I sent you a complete copy of the AFAPL report last October. The proposed experimental work will require the use of an efficient radiant source(s) in the VUV spectral region from 140 nm to 200 nm operated in the pulsed mode, and in the UV spectral region approximately from 200 nm to 400 nm operated in the continuous mode. In order to avoid the light source difficulties encountered in the past AFAPL program, we are seeking qualified light source suppliers to provide reproducible ultraviolet light sources with reasonable operating life for research experiments. VUV source requirements are outlined in Attachment B and may necessitate a short (estimated 6 months) development program. UV source requirements are outlined in Attachment C and should be available as standard (or slightly modified) items.

I would appreciate a response as soon as possible regarding your interest in supplying one or more of the indicated sources. Please advise regarding delivery schedule, source energy flux in the wavelength regions of interest, source size, estimated reproducibility and life, cost, and power supply. I plan to evaluate candidate sources over the next four week period and select the most suitable for program use. As I indicated on the phone, I would like to visit your facility following your response for further discussion about the third week of September.

If you have any questions or desire additional information, please call me at Exxon Research and Engineering Company at (201) 474-2912.

Sincerely yours,

Anthony E. Cerkanowicz

AEC/jep

Attachments

ATTACHMENT A

PHOTOCHEMICAL COMBUSTION BACKGROUND MATERIAL

DISSOCIATION MECHANISM

Photochemical ignition involves the initiation of rapid combustion reactions through the photodissociative creation of high nonequilibrium concentrations of an important intermediary in the reaction kinetic scheme. Initiation is thus achieved without the need for heating the mixture and without the attendant heat loss mechanisms. Consequently, a new class of ignition characteristics is experienced as compared with standard thermal initiations. The intermediary of major importance in initiation of practical combustion reactions is atomic oxygen, which can be efficiently produced by photodissociation of molecular oxygen with light below 1800 $\overset{o}{A}$. Subsequent reaction of the atomic oxygen with fuel molecules (at an initial temperature of 300° K) leads to sustained combustion, when oxygen atom concentrations on the order of 10^{14} atoms/cm^3, or greater, are generated. Experience indicates that the radiant energy consumed for photochemical ignition by this process is only on the order of $\mu J/100 \overset{o}{A}$ at 1500 $\overset{o}{A}$. The kinetic sequence for ignition is thus given by the following reactions;

$$O_2 + h\nu \rightarrow O + O$$

$$O + fuel \rightarrow chain\ reactions$$

$$chain\ reactions \rightarrow products$$
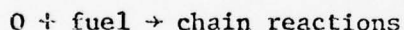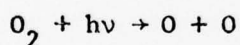
Since this form of photochemical ignition relies on dissociation of oxygen, the principle is applicable to a wide variety of fuels. Photochemical ignition at room temperature of hydrogen, carbon monoxide, methane, acetylene, commercial gasoline, and varsol (kerosene) has been demonstrated successfully, thus supporting the potential application of photochemical ignition to a wide variety of fuels.

EXPERIMENTAL IGNITION CHARACTERISTICS

Threshold energy requirements for photochemical ignition of the fuels listed previously (liquids in the atomized state) varies depending on the fuel and the oxidant combination tested. Higher hydrocarbons require slightly higher energies, and air requires slightly higher energies. However, for all possible fuel-oxidant variations, the photochemical ignition threshold energy requirements are of the same order of magnitude. Changing the mixture stoichiometry from stoichiometric to fuel-lean results first in a threshold energy decrease, then an increase (Figure 1). Again, however, the variation in threshold energy requirement is well within an order of magnitude, even beyond the stoichiometry range indicated. For example, the energy typically required for photochemical ignition is increased by a factor of only 2 for a 16-fold decrease in fuel concentration. A comparison of photochemical ignition with thermal (spark) ignition for lean mixtures (Figure 2) illustrates the vastly different characteristics that can be obtained by using the photochemical technique.

The required threshold energy level for photochemical ignition as a function of pressure has a relatively flat minimum between approximately 5 and 15 psia, but increases sharply at pressures below 2 psia (see Figure 3). An increase of pressure to above 80 psia is necessary before a two-fold increase in energy above the minimum value occurs. The majority of the photochemical ignition experiments have been performed at initial temperatures of about 80° F. However, on the basis of some limited experiments at slightly elevated temperatures, and analytical considerations of kinetic requirements at increased temperatures, it is expected that photochemical ignition energy requirements decrease rapidly with increasing temperature.

The effect of flowing the reactant mixture past an optical window through which the photodissociative energy is transmitted is illustrated in Figure 4. Photochemical ignition energy threshold vs. mixture velocity curves are presented for gaseous hydrogen-oxygen and hydrogen-air mixtures as well as for atomized gasoline-air mixtures. (Successful preliminary experimental runs using kerosene have also been performed.) Required photochemical ignition energy remains essentially constant as the mixture velocity is increased above zero until some critical velocity is reached. A linear increase of ignition
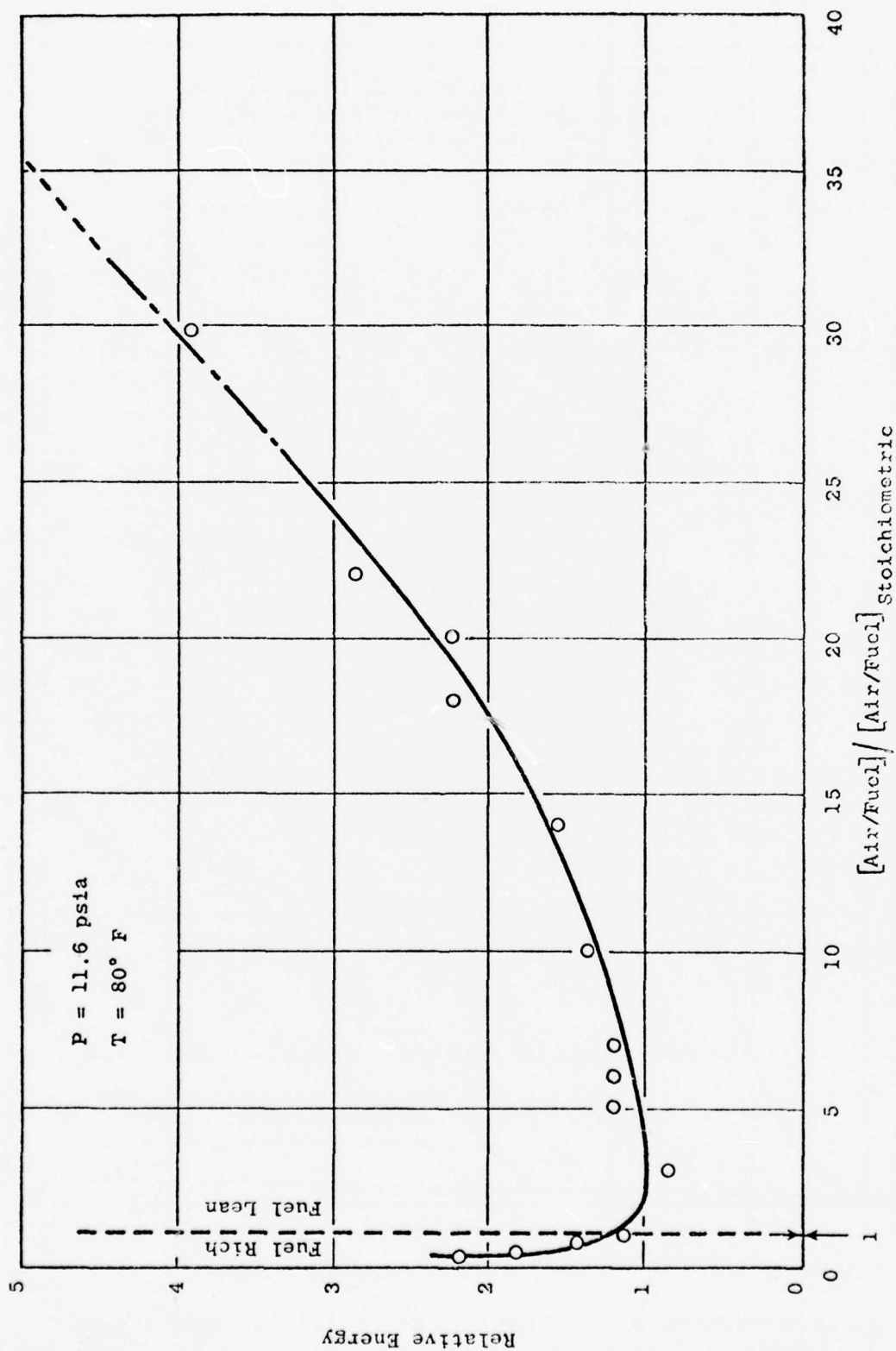
Figure 1. Relative Photochemical Initiation Energy for Mixtures of Hydrogen and Oxygen as a Function of Normalized Air-Fuel Mixture Ratio.
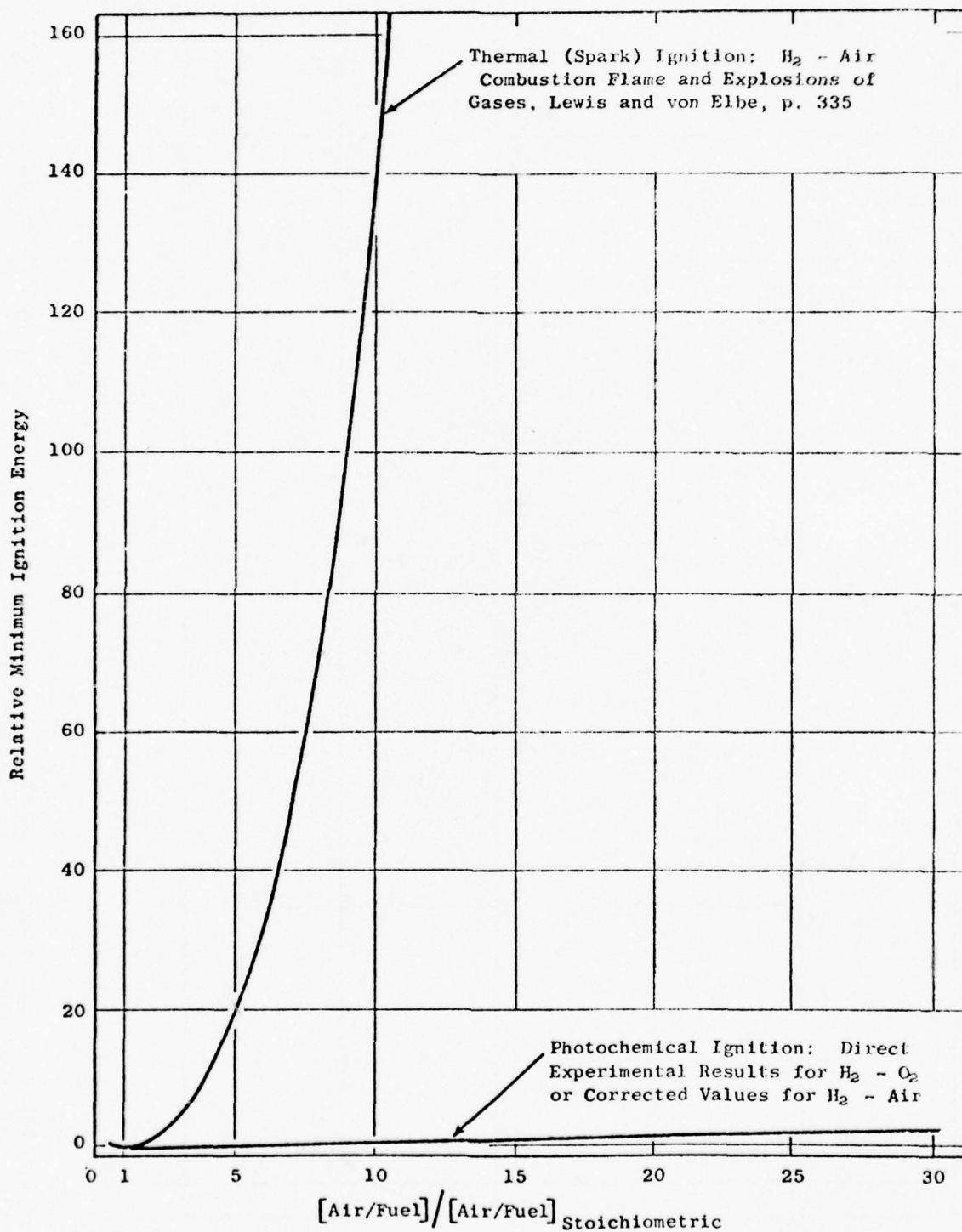
Figure 2. Comparison of Minimum Ignition Energy Versus Air/Fuel Ratio
Curves for Thermal (Spark) Ignition and Photochemical Ignition.
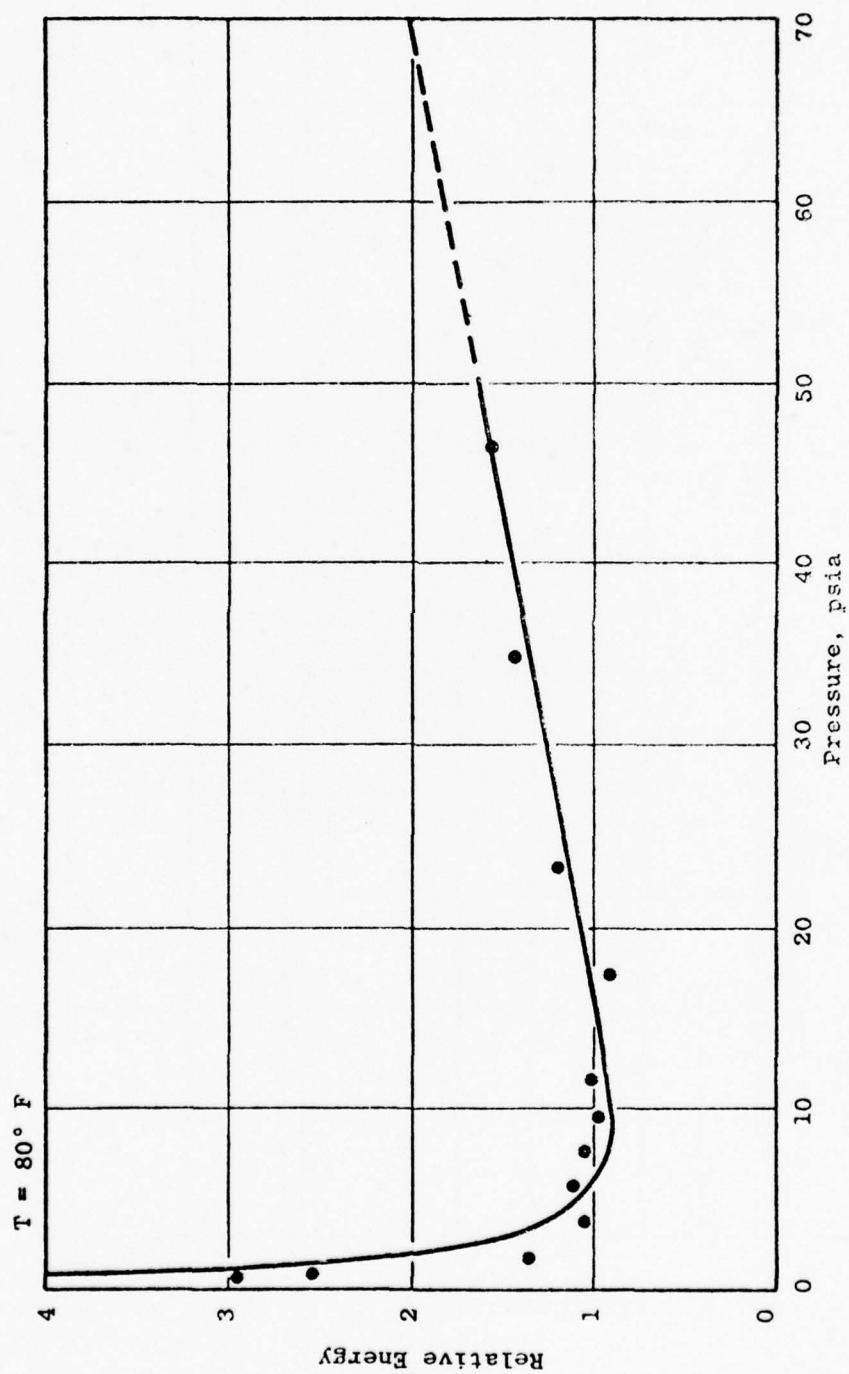
Figure 3. Relative Photochemical Threshold Initiation Energy as a Function of Pressure for Stoichiometric Mixtures of Hydrogen and Oxygen.
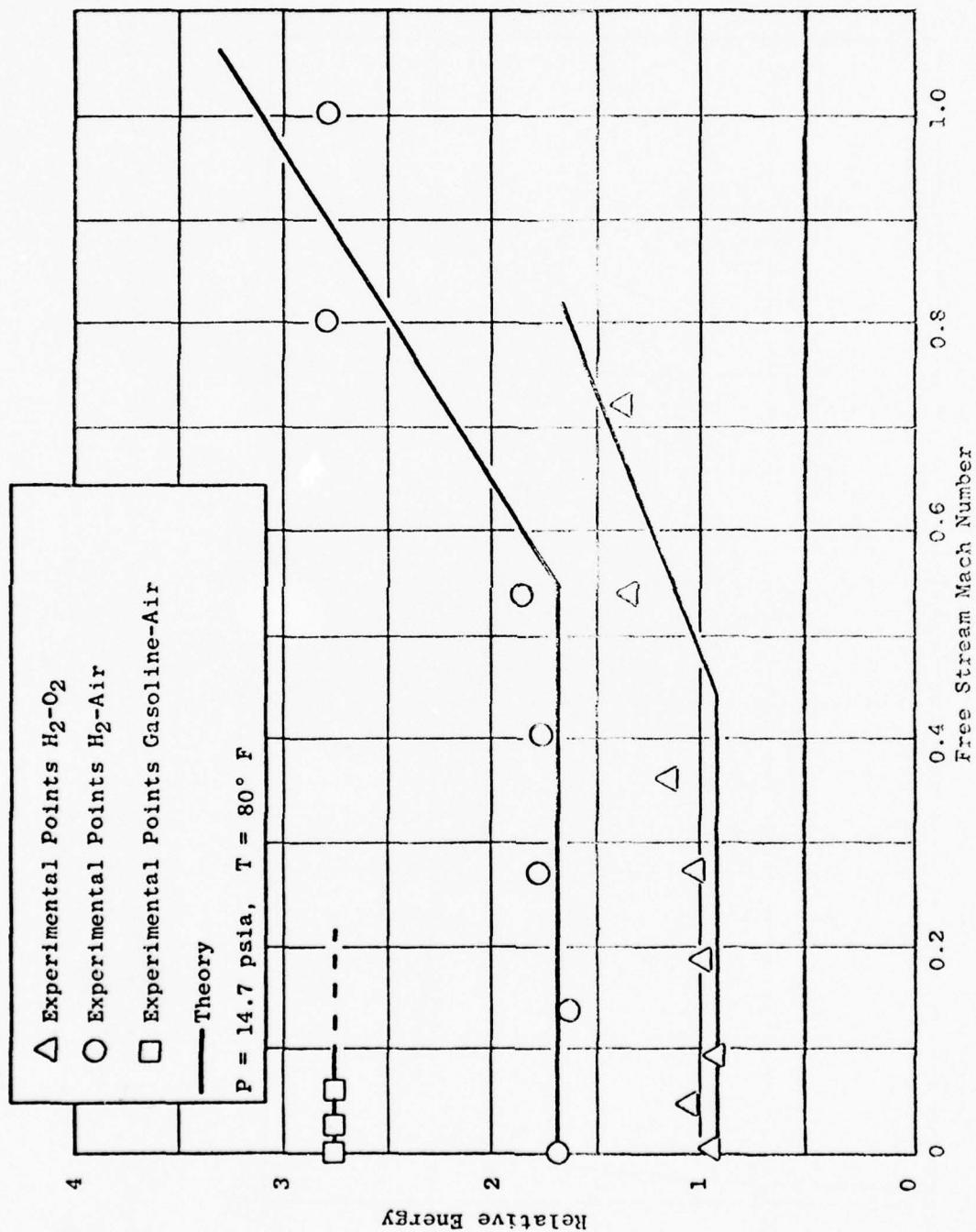
Figure 4. Relative Photochemical Threshold Initiation Energy as a Function of Velocity for Various Mixtures.

energy requirements with increasing mixture velocity is experienced for flows above the critical value.

Photochemical ignition delays of 0.1 to 1.0 msec have been measured for hydrogen and methane fueled mixtures at an initial temperature of about 80° F. Variation of the delay with stoichiometry, pressure, or temperature is similar to that observed for the threshold ignition energies. Measured velocities of photochemically initiated flame fronts are greater than corresponding thermally initiated fronts.

Although the data presented herein pertain mainly to hydrogen fueled mixtures, all fuels tested exhibited essentially the same ignition characteristics.

THEORETICAL ANALYSIS OF PHOTOCHEMICAL IGNITION

Extensive analytical work has been accomplished which supports the experimental results. The effect on ignition energy requirements of mixture type, stoichiometry, pressure, temperature, and flow velocity have been analytically defined. The influence of the various light source parameters (window material, pulse time, etc.) also have been studied analytically. Analysis of the energy required to ignite, photochemically, flowing mixtures as a function of velocity results in predictions which adequately fit the data points and demonstrates the occurrence of a critical flow velocity (see Figure 4), thus providing a basis for reliable extrapolation of the photochemical ignition characteristics to regions where data are presently lacking.

Analysis of the depth of penetration of the photochemical effect for various conditions yields results similar to those shown in Figure 5. As can be seen, the oxygen atom concentration produced is maximum near the window and decreases with distance from the window into the mixture. At threshold photochemical ignition energies, the critical oxygen atom concentration (10^{14} atoms/cm^3) is produced near the window, and, thus, ignition will originate in this region. In this case (threshold ignition energy), the oxygen atom concentration at a penetration distance of about one foot into the mixture will be down three orders of magnitude (10^{11} atoms/cm^3). However, although this concentration is insufficient for direct ignition, it does result in a combustion enhancement effect since the temperature increase required for ignition is lowered to only
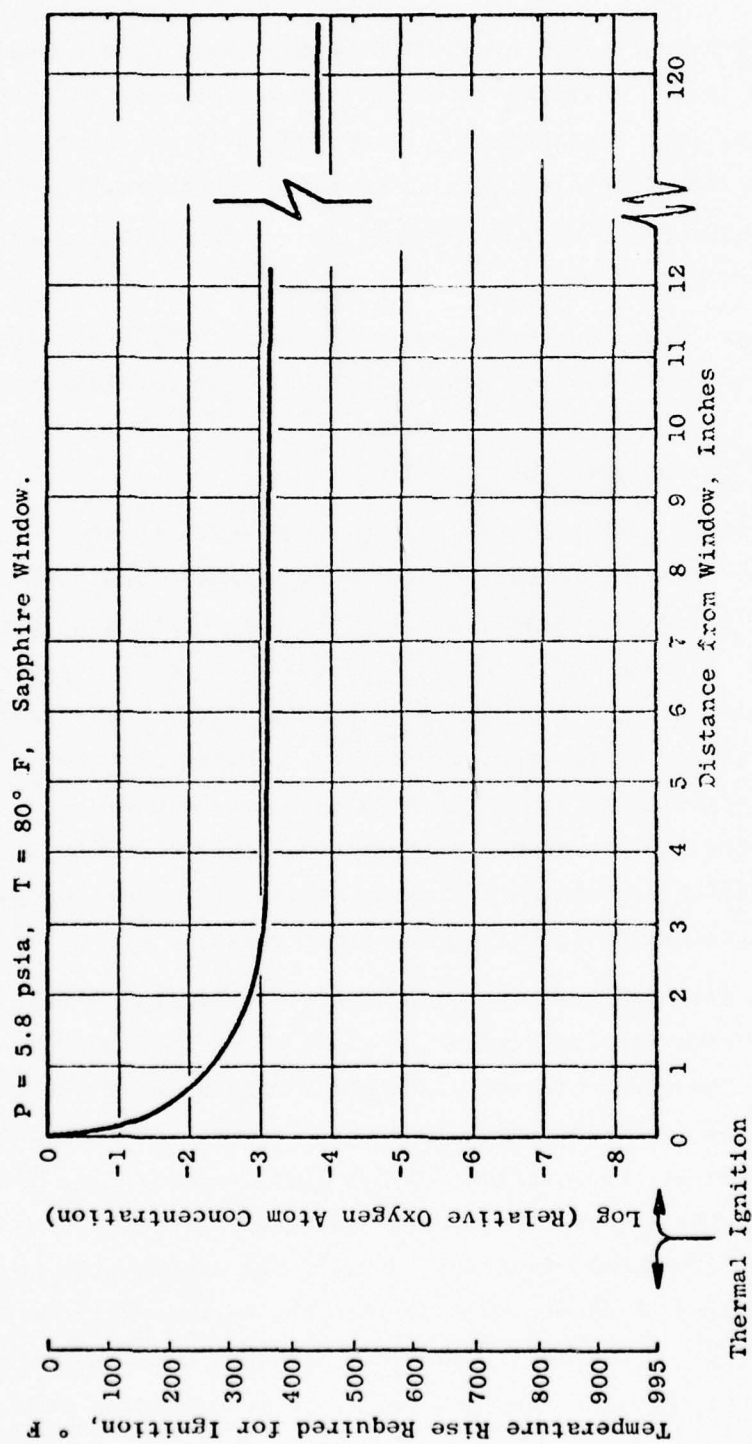
Figure 5. Penetration of Photodissociation and Combustion Enhancement Effects as a Function of Distance from Window for Stoichiometric Mixtures of Hydrogen and Oxygen.

325° F, as opposed to the 995° F normally needed for thermal ignition. Even at a distance of 10 feet into the mixture, sufficient oxygen atoms (greater than 10^{10} atoms/cm^3) are present to lower the required temperature rise for ignition to only 430° F.

Further, increasing the radiant energy input above the threshold ignition level raises the penetration curve proportionately, thus increasing the ignition and combustion enhancement effect at any given distance into the mixture. For example, for radiant inputs 100 times the threshold level (within present capability), photochemical ignition sites (oxygen atom concentrations greater than 10^{14} atoms/cm^3) would be created over a distance of 0.75 inch from the window (for the condition in Figure 5). Consequently, if the initial part of this region was a fuel-free layer of air, ignition would still occur in the in-depth region. Additionally, the enhancement effect at greater distances into the mixture would also be increased, lowering the required temperature rise for ignition to only about 100° F.

Use of a photochemical igniter positioned in the side wall of a combustor will require that the radiant flux penetrate a fuel-free boundary layer of air. Consequently, oxygen atom concentrations sufficient for photochemical ignition must be produced at some finite distance into the mixture. As shown in Figure 6, this requires an increase in the radiant energy input, the value of which depends on the thickness of the air layer. For boundary layers of about 1/8 inch, less than an order of magnitude increase in the radiant energy would be required. Such increases are entirely within the realm of practical light source design.

IGNITER DESIGN ANALYSIS

The radiant source employed for an ignition device should effectively produce radiant energy in the oxygen photodissociation region which extends from below 1000 Å to 2450 Å. However, the practical lower limit is determined by the characteristics of available ultraviolet (UV) transmitting windows (see Figure 7 and Table 1). The best UV transmitting materials are fluorides which, unfortunately, are water soluble and hydroscopic with softening points between 750 and 1100° F. For practical applications, sapphire provides the
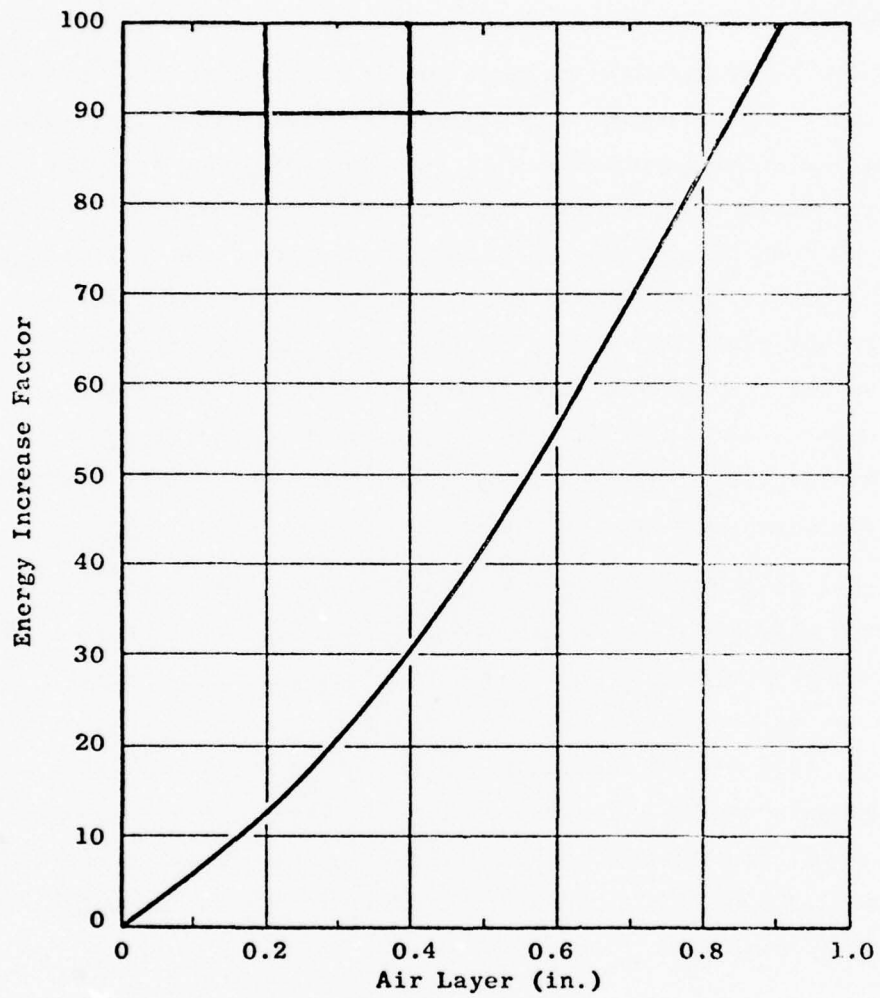
Figure 6. Energy Increase Required to Achieve Photo-
chemical Ignition after Penetration of an Air
Layer at 1000° F and 1 Atmosphere.

- 31 -
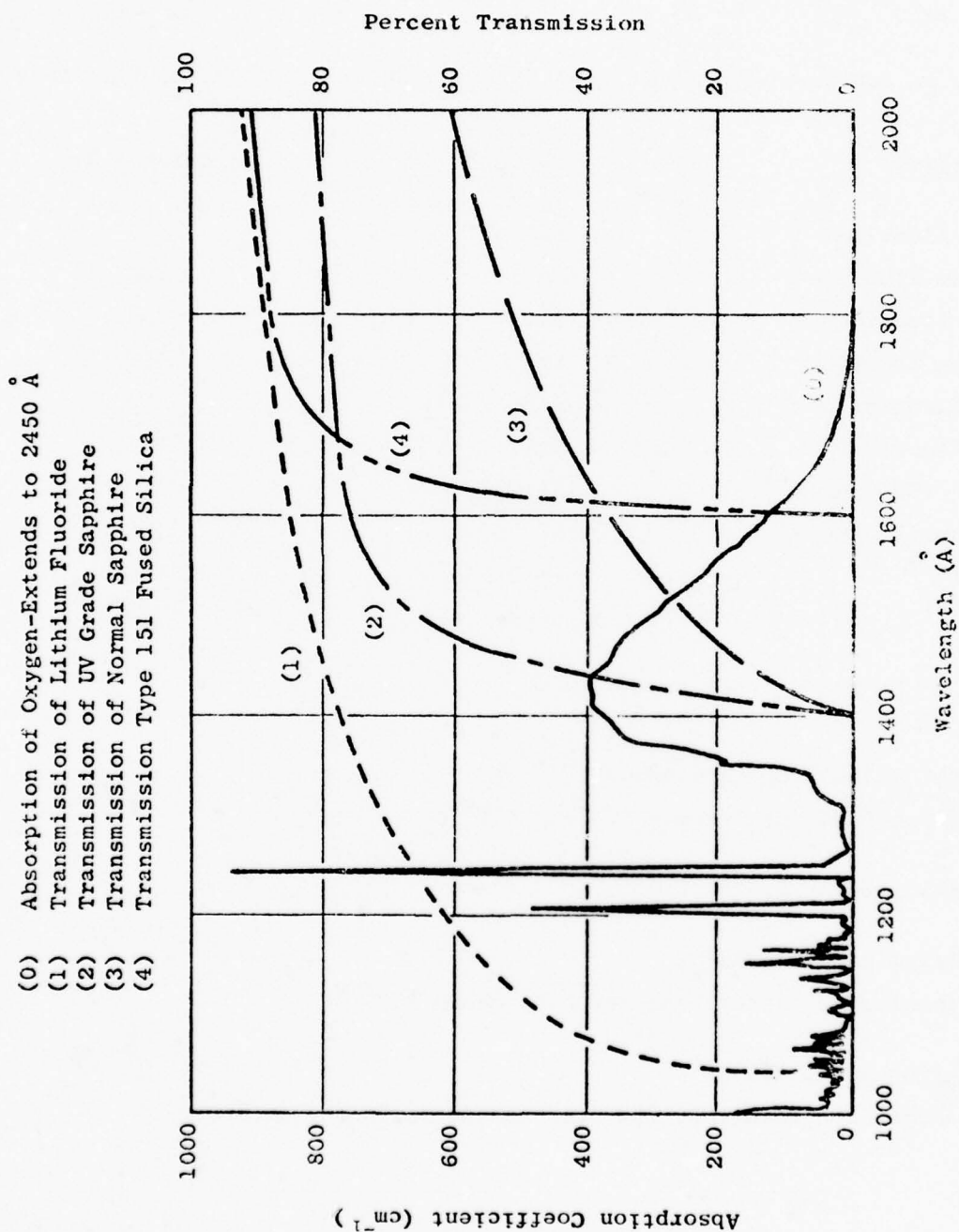
Figure 7. Superposition of Window Transmission and Molecular Oxygen Absorption in the Wavelength Range 1000 Å to 2000 Å.

(0) Absorption of Oxygen-Extends to 2450 Å
(1) Transmission of Lithium Fluoride
(2) Transmission of UV Grade Sapphire
(3) Transmission of Normal Sapphire
(4) Transmission Type 151 Fused Silica

Table 1. Low Wavelength Cutoff of Various Far-UV Transmitting Materials

Material	Formula	Cut-off $\overset{\circ}{A}$
Lithium Fluoride*	LiF	1040
Magnesium fluoride*	MgF_2	1100
Calcium fluoride*	CaF_2	1250
Strontium fluoride*	SrF_2	1300
Sodium fluoride*	NaF	1300
Barium fluoride*	BaF_2	1345
Sapphire (UV Grade)[1]	Al_2O_3	1400
Potassium fluoride*	KF	1600
Suprasil[2]	----	1600
Lucalux[3]	----	1700

Notes:

* Water soluble and hydroscopic

    Softening points between 400 and 600° C

(1) Melting point 2,040° C

(2) Melting point 1,800° C

    Transmission better than sapphire above 1680 $\overset{\circ}{A}$

(3) Melting point 2,040° C

    Transmission less than 20% over entire region of interest

best UV transmitting material (lower cutoff at 1400 Å). When the absorption curve for molecular oxygen is considered, the wavelength range of interest is further narrowed due to the efficiency of photodissociation. For the region close to the window, 0 to 0.004 inches, the effective wavelength range is 1450 to 1650 Å, while in the region from 0 to 1 inch the effective wavelength range is 1450 to 1800 Å. If, however, it is of interest to enhance combustion at greater distances into the mixture, oxygen absorption at higher wavelengths is also important. Far from the window, 1 to 12 inches, the effective wavelength range is 1650 to 1850 Å, while in the region from 1 to 10 feet the effective wavelength range is 1750 to 2450 Å. In these latter regions, quartz windows are more efficient than sapphire windows.

A typical configuration of radiant source design, shown in Figure 8, is a high pressure arc (50-150 psia argon) designated PC-4. This design is capable of producing the radiant energy necessary for photochemical ignition (µJ/100 Å at 1500 Å) using sapphire windows. The PC-4 configuration shown requires inputs on the order of tens of joules or less. The trends in required energy level improvements of sources are shown in Figure 9.

Bibliography

Cerkanowicz, A. E., "Photochemical Initiation of Sustained Combustion in Unsensitized Gaseous Fuel-Oxygen Mixtures", Ph.D. Dissertation (Univ. Mic. No. 71-1161), Stevens Institute of Technology, June, 1970.

Cerkanowicz, A. E., "Photochemical Enhancement of Combustion and Mixing in Supersonic Flows", AFOSR Final Report TR-74-0153, November, 1973.

Zettle, E. V., "Exploratory Investigation of Photochemical Ignition for Turbine Engine Combustors", AFAPL-TR-74-87, October, 1974.
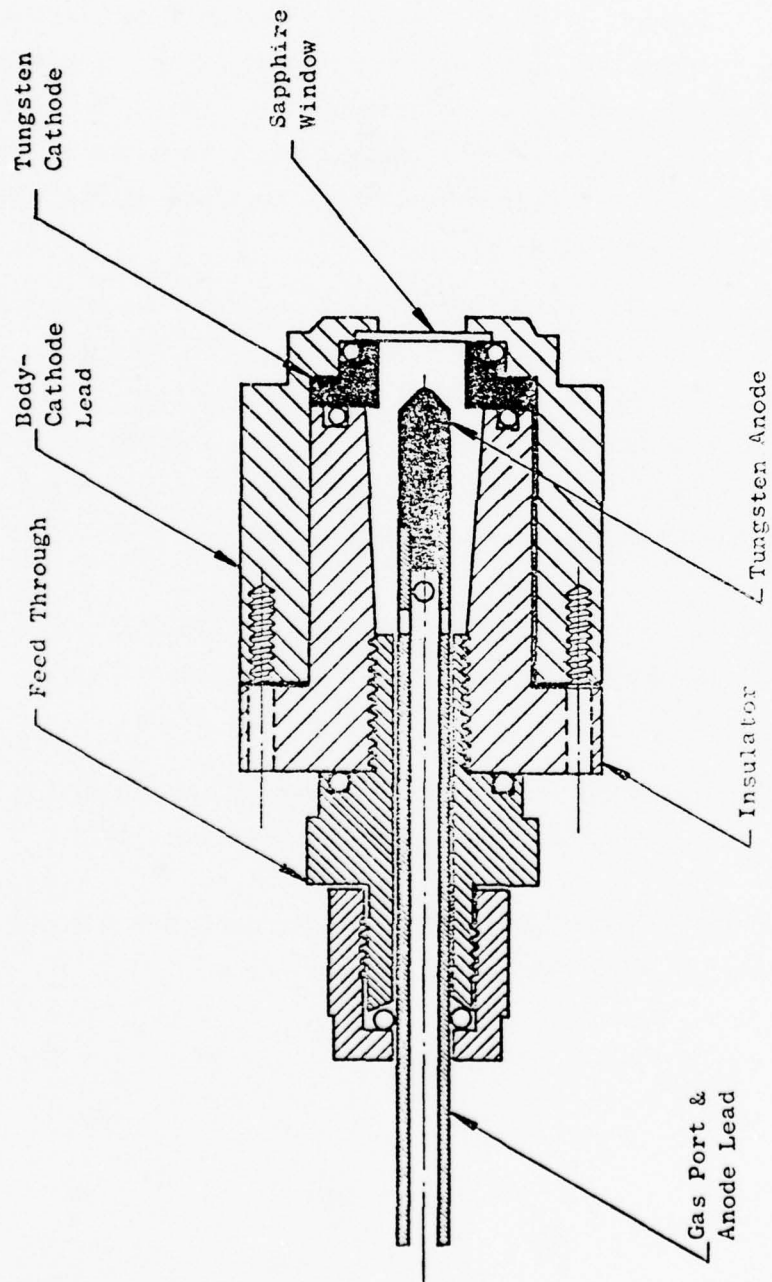
Figure 8. PC-4 High Pressure Arc Igniter, 2X Full Scale.
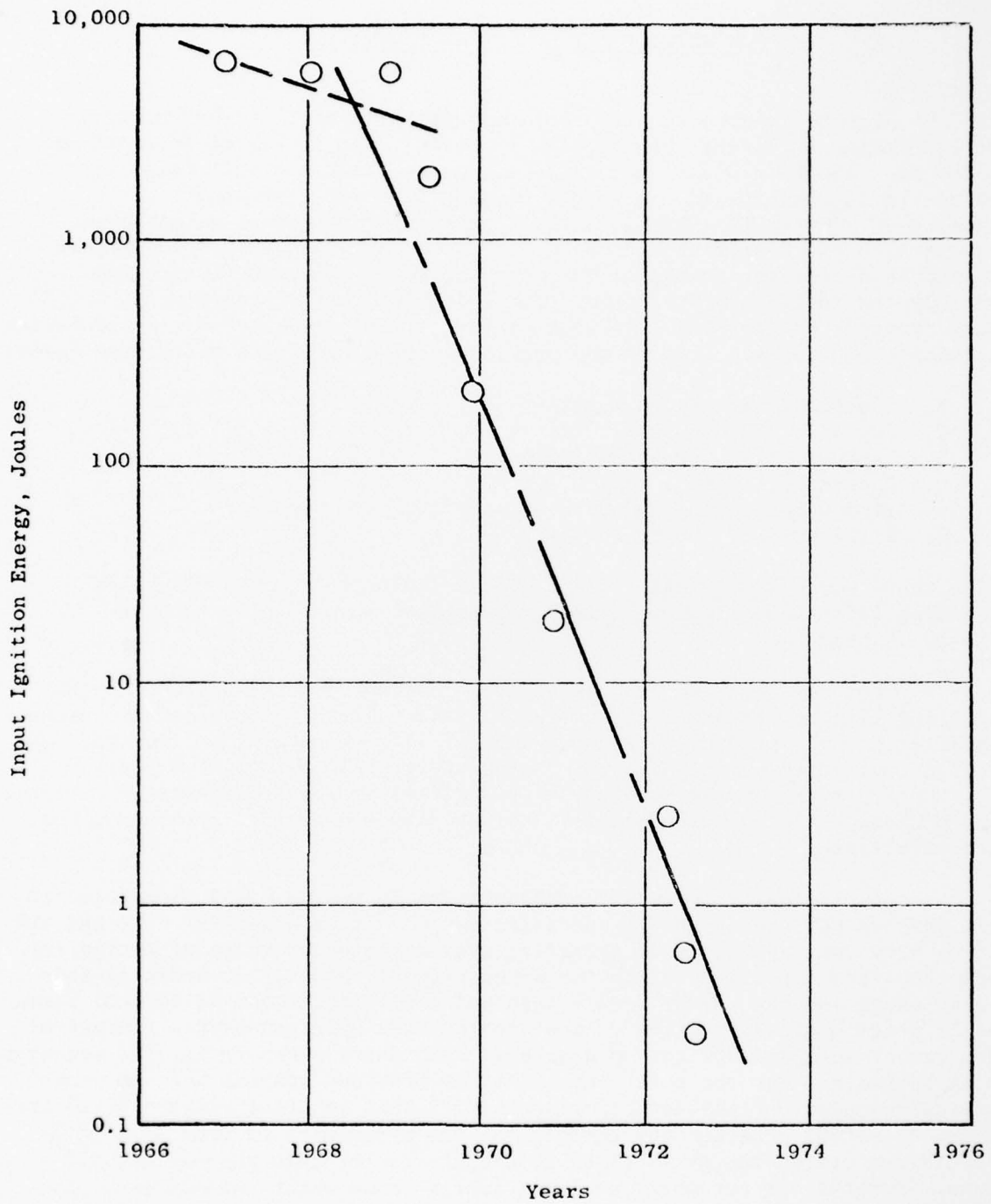
Figure 9. Rate of Development of Improved UV Light Sources for Photo-
chemical Ignition (Standard H_2-O_2 Calibration Mixture).

ATTACHMENT B

VACUUM ULTRAVIOLET SOURCE REQUIREMENTS

The VUV source required for combustion initiation must provide for generation of intense photon flux in the wavelength region from 140 nm to 200 nm. Sapphire window material will be required and wall mounting of the source is anticipated. A window opening of about 0.25 inches diameter or greater is typical. Single pulse operation will be employed. Figures 1, 2 and 3 extracted from an Air Force Report (AFAPL-TR-74-87) can be used as a starting point for defining the source characteristics and possibly the design configuration. These drawings are representative scale drawings of the most efficient sources utilized in previous photochemical ignition experiments. Some of the previous design specifics are listed below:

1. Electrode material - tungsten
2. Gap size $\approx$ 0.060 inch
3. Igniter fill pressure - 200 psia
4. Igniter fill gas - Xenon
5. Window material - 0.040-inch thick UV-grade sapphire
6. Pulse period - 50 to 100 μs

While these sources were efficient they did suffer from extremely short operating life-time. Improved life or substitution with other source designs is needed.

For the research program underway, a reproducible source with an operating life on the order of several hundred pulses is satisfactory. (Final application would eventually require a pulse life of several million and some limited repetitive pulse operation on the order of 10 pulses at 1 pps.) The source design offered need not be restricted to those illustrated. Source quotes should also contain details, availability and cost of power supplies where available.

A critically important consideration in source design and selection will involve VUV source energy operating range. It is essential that the VUV source have the capability of operating over an extended range of energy input (and therefore output) to allow for unknown requirements. In defining this energy range and the energy levels involved a reference case is defined based on the photochemical ignition of a stoichiometric hydrogen-oxygen mixture at room temperature and 300 torr pressure (1 atmosphere pressure is also acceptable). It is estimated that the total output of the previous sources used in photo-chemical combustion ignition experiments with this reactant mixture (0.25 inch window diameter) produced VUV energies on the order of 4 μJ/100Å at 1500 Å. The minimum stored energy supplied to the source for this purpose was 1/4 joule. For the subject work, an input energy range which extends from that sufficient for ignition of the standard mixture to 100 times that value is required. Thus, if ignition of the standard mixture is achieved with 1 joule input energy levels then the source should also be capable of reliable operation at energy levels of at least 100 joules. This specification assumes that a linear relationship exists between total input energy (as measured by the amount of energy stored in a capacitor bank) and the total photon energy output in the VUV region between 140 nm and 200 nm.

Reference

Zettle, E. V., "Exploratory Investigation of Photochemical Ignition for Turbine Engine Combustors", AFAPL-TR-74-87, October, 1974.
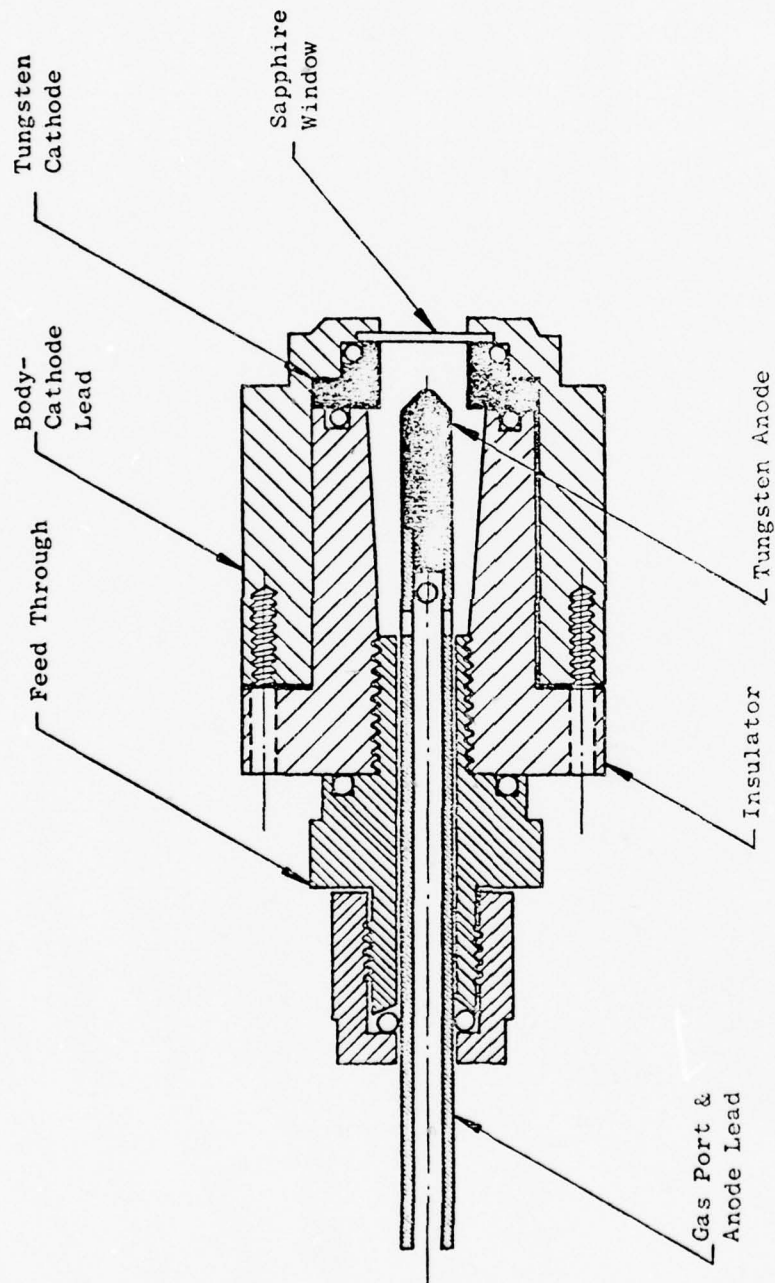
Figure 1. PC-4 High Pressure Arc Igniter, 2X Full Scale.
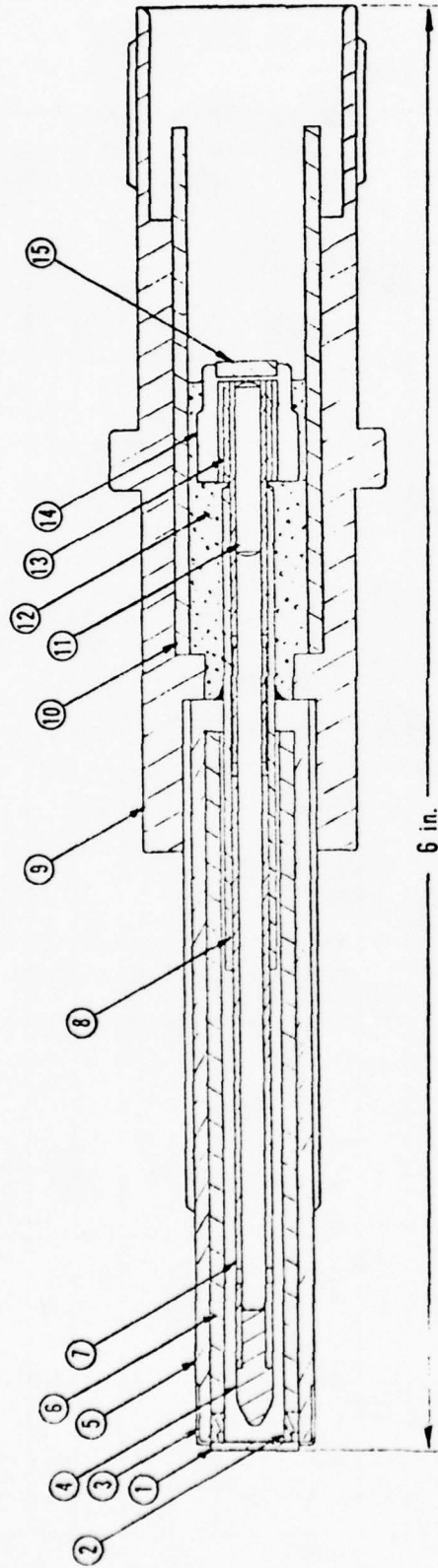
PART	MATERIAL
1	Sapphire
2	Tungsten 2% Th
3	Kovar
4	Tungsten 2% Th
5	Kovar
6	Alumina
7	Molybdenum
8	Alumina

PART	MATERIAL
9	Stainless Steel
10	Alumina
11	Stainless Steel
12	Epoxy
13	Stainless Steel
14	Brass
15	Tungsten 2% Th

Figure 2. Modified PC-4 Igniter (PC-4A).
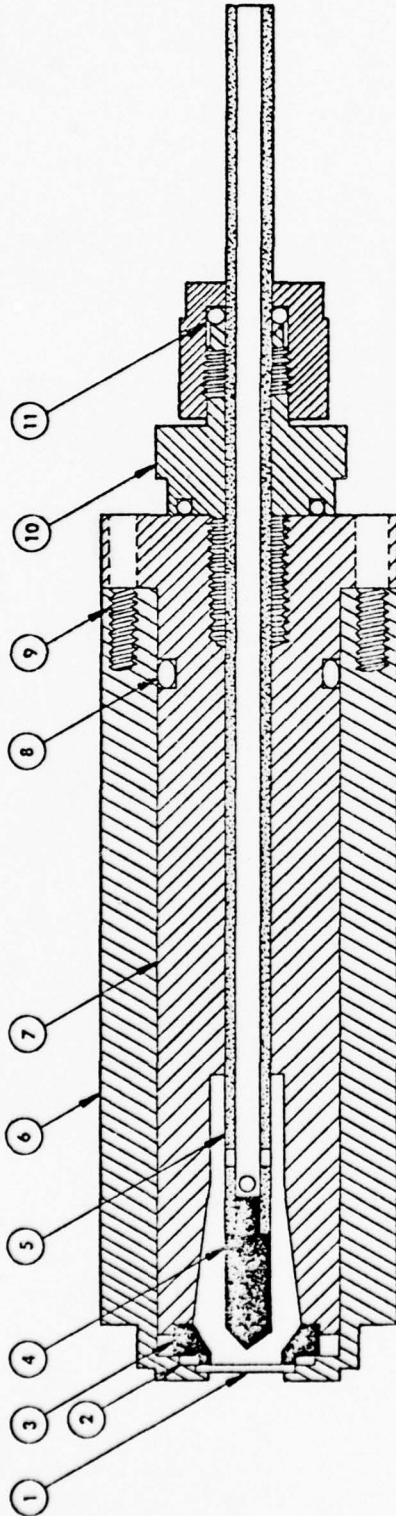
PARTS LIST

ITEM	DESCRIPTION	MATERIAL	NOTES
1	Igniter Window	Sapphire	U.V. Grade - Union Carbide - 0.375 Dia
2	O-Ring Window Seal	Silicon Rubber	2-011-Parker
3	Ring Electrode	2% Th-W	½ Dia.
4	Center Electrode	2% Th-W	5/32 Dia.
5	Feed-Thru	316 S.S.	0.156 O.D. by 0.111 I.D. Tubing
6	Igniter Body	Aluminum	1.0 Dia.
7	Body Insulator	Supramica	1.0 Dia.
8	O-Ring Body Seal	Silicon Rubber	2 - 014 - Parker
9	Screws	Steel	4/40 by 3/8 Long
10	Feed-Thru Fitting	Nylon	NY-200-1-OR-Swagelock-Drilled for 5/32 Tube
11	O-Ring Feed-Thru Seal	Silicon Rubber	2-009-Parker

Figure 3. Cross-Sectional View of the PC-43 Photochemical Igniter.

ATTACHMENT C

ULTRAVIOLET SOURCE REQUIREMENTS

Radiative enhancement of combustion requires the generation of intermediate combustion species at lower concentrations than required for combustion initiation[1]. Further, VUV radiation (below 200 nm) is not necessary. The in-depth generation of low level concentrations of oxygen atoms for enhancement can be achieved with 200 nm to 245 nm radiation. Also, Norrish[2], has demonstrated combustion enhancement by irradiation with UV light (200 nm to 400 nm). Norrish attributed the observed enhancement effects to formaldehyde dissociation which required 270 nm to 350 nm radiation. Consequently, enhancement does not require VUV radiation and can be achieved with less intense continuous UV sources. Depending on the combustor-UV source geometrical configuration, an additional benefit could be realized by the time integrated effects of steady irradiation.

Continuous, broad band, UV light sources are sought which maximize the radiant energy flux available in the 200 nm to 400 nm region and more specifically, the 270 nm to 350 nm region. Preferably, (but not necessarily), the UV sources should be wall mountable and utilize sapphire window material. Window diameters can range between 0.5 to 2 inches. Reflecting optics is permitted and both parallel and focused beam will be considered. If necessary, more than one UV source may be proposed in order to cover the wavelength range of interest. Required power supply equipment should also be specified with costs as available. It is anticipated that several sources or systems with UV capability will be purchased.

References

1. Cerkanowicz, A. E., "Photochemical Enhancement of Combustion and Mixing in Supersonic Flows", AFOSR-TR-74-0153, November, 1973.

2. Norrish, R. G. W., "The Study of Combustion by Photochemical Methods", Plenary Lecture, Tenth Symposium on Combustion, pp. 1-18, 1965.

ATTACHMENT D

ILC Technology

P-ILC-77-5   January 1977

UV COMBUSTOR
LIGHT SOURCE DEVELOPMENT

Prepared for: Exxon Research and Engineering Comapny
Government Research Laboratory
Advanced Energy Systems Laboratory
P.O. Box 8
Linden, New Jersey   07036
Attention: Dr. A.E. Cerkanowicz

Prepared by: Staff of ILC Technology, Inc.

Approved by:

Dr. Leonard Reed, Vice President

BACKGROUND

Considerable effort has gone into studying UV sources to trigger combustion in various fuel-oxygen mixtures. It has been shown that combustion can be triggered by radiation pulses of roughly 10 μJ in the 145 nm to 165 nm region. In particular, it has been demonstrated that rarefied gas mixtures can be ignited under conditions normally thought to preclude burning. Further, the actual energy required for ignition has been shown to be as low as 1% of that required for normal spark ignition. These characteristics make the UV combustor a promising source for supersonic combustion applications where no effective igniter is now available. There are, however, problems peculiar to this type of device that need consideration.

The vacuum ultraviolet is not familiar ground for most scientists and certainly not for most lamp manufacturers. As a consequence, combustor window materials cannot be conventional and quantitative measurements of combustor output have been difficult to make. The principal absorbtion band of oxygen is between 135 and 165 nm and to get full transmission though this band, it is necessary to use a window material like LiF. In practice, it proves preferable to use UV grade sapphire that only transmits half as much energy but can withstand the pressure and stress of a combustion environment. Likewise, quantitative measurements of radiation output are difficult to make especially when looking for pulse outputs of 1 mJ or less. There are no calibrated standard radiation sources below 250 nm, so absolute measurements usually require some degree of extrapolation. Even now it is impossible to write a definitive specification for a combustor source because of this lack of data.

Finally, previous efforts have paid insufficient attention to developing a repeatable radiation source with long life. This has prevented the generation of reproducible data and led to severe experimental difficulties. It is now clear that developing a high

temperature, UV resistant, reproducible source is a key requirement
for any future development programs. This source should produce
between 10 μJ and 1 mJ in the 135 to 165 nm region, be capable of
million shot life, and have a reasonable cost in quantity.

ILC Technology Inc. has the critical technology for developing
a reliable device of the type described. ILC is a major supplier
of xenon flashlamps and is probably the leading supplier of custom
designed lamps. The materials processing and cleanliness require-
ments for your application will be similar to those for flashlamps
that we make on a routine basis.

Perhaps more crucial is the fact that ILC has developed pro-
prietary ceramic metal sealing techniques to allow the construction
of a hermetically sealed light source capable of high temperature
processing and operation. As a graphic example of our capability,
ILC is now building for the Air Force a series of alkali metal
pump lamps with sapphire envelopes and air compatible ceramic to
metal seals that operate at temperatures to 800°C. At present,
these lamps have demonstrated a life in excess of 1,500 hours in
air and, with design refinements now being incorporated, we expect
to achieve 3,000 hours life. As another example, ILC is building
a sapphire envelope xenon flashlamp for an Army rangefinder system
that requires high lamp operating temperature.

From your letter and the AFAPL report you sent me, I take
your basic requirement to be the following:
  1. Radiation output 145 to 165 nm variable for 0.01 mJ to
      1.0 mJ with less than 100 μsec pulsewidth.
  2. Approximate energy input 100 mJ to 10 J at 2 pps.
  3. Lifetime of 1000 shots minimum.
  4. Design goal life of 2 million shots.

There is high confidence that a long life device can be built
at this power level in the 20 watt size. We have never measured

vacuum ultraviolet output from our lamps (quartz cuts off at about
160 nm), but we have other relevant information. Measured output
from a light source built for the Stanford Linear Accelerator Center
(SLAC) shows an output of 30×10^{-5} J/ster-nm-pulse for a 2 to 5 J
pulse at 200 nm. The curve is fairly flat at this point and if
extrapolated to the 150 nm range would yield 6 mJ/ster from 145 to
165 nm. Assuming 3.5 ster output gives roughly 20 mJ/pulse for a
2 to 5 J pulse. Admittedly, this is only a rough calculation but
the apparent factor of 20 margin of safety lends credence to the
claim that this output level is feasible.

From previous experience, it would appear that decreasing the
pressure of the combustor source and increasing the peak current
would enhance the UV output of the device. Figure 1 shows a pre-
liminary test device that would be relatively easy to build. It
uses a standard ILC flashlamp cathode and sapphire window assembly.
UV grade sapphire will be used in the window. Voltage standoff is
provided by the alumina end member. The outside diameter of this
device is larger than originally planned in order to get more stand-
off distance between the body and cathode and to use an assembly
more suitable for welding during final assembly.

This device will differ from previous UV light sources in
being filled with subatmospheric pressure xenon and being inter-
nally triggered. This device should be run at a minimum of 5 kV
to get a pulsewidth of less than 20 μsec. Triggering will probably
be achieved with a spark gap. Since ILC instrumentation is limited
to 200 nm, radiometric optimization will be done at this wavelength
assuming that the gas is radiating as a continum and that high out-
put at 200 nm indicates high output at 155 nm.

PROPOSED PROGRAM

In the proposed program, ten devices would be fabricated and
then filled and tested sequentially. When a reasonable optimization

FLASHLAMP CATHODE

TUNGSTEN

KOVAR

SAPPHIRE
S-4-5

1.242

1.064

NICKEL

ALUMINA

KOVAR
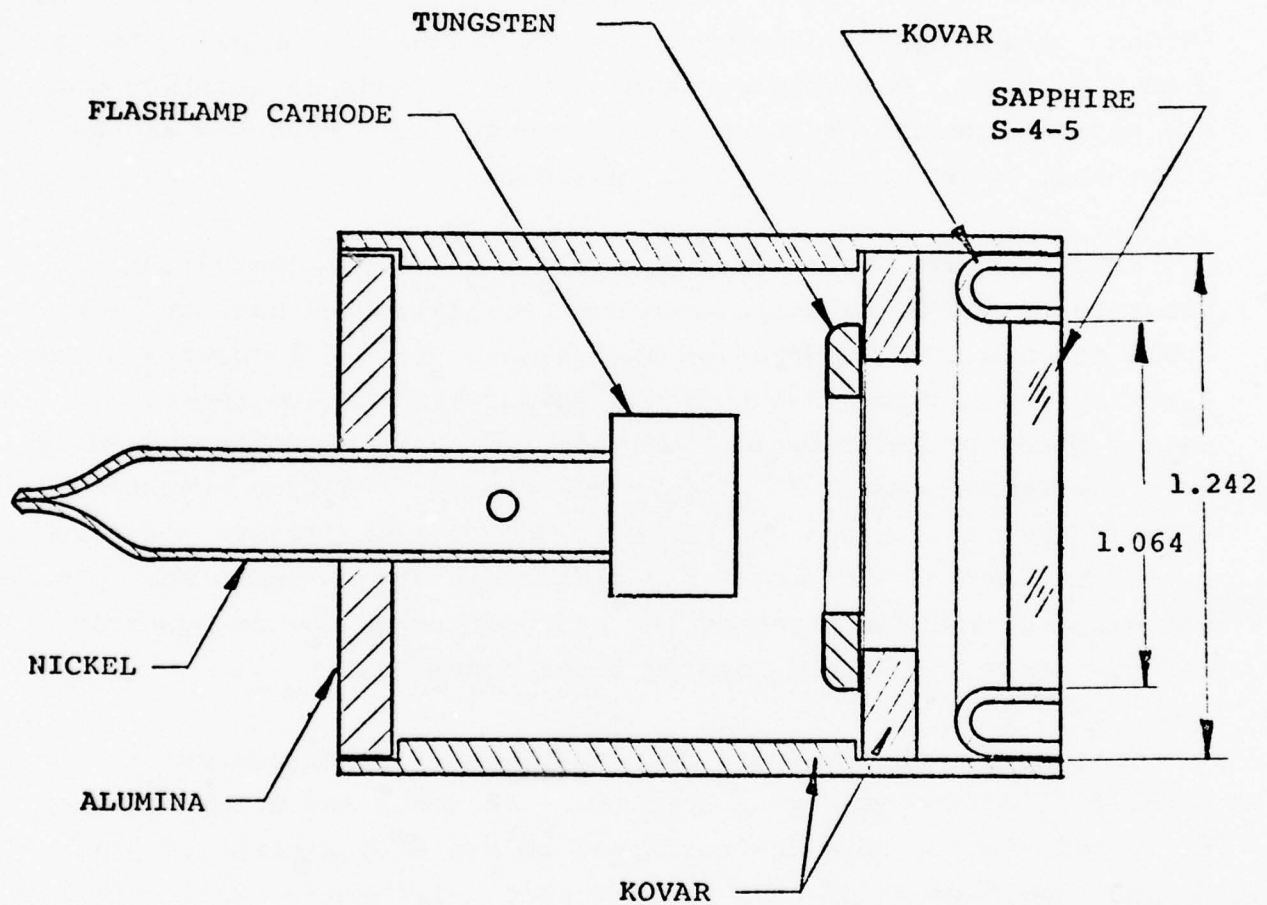
FIGURE 1

UV COMBUSTOR PRELIMINARY TEST LAMP

has been achieved, two devices would be life tested. The original
design would be modified based on the life and optimization test
results. Twelve more devices would be built and filled and two
checked for performance and life. It will require six months to
fabricate the first design, take data, redesign the unit, and pro-
duce ten deliverable units.

COSTS

The costs involved are as follows:

1.	Build ten devices as in Figure 1.	$ 5000
2.	Take optimization data on at least six devices and life test data on at least two devices.	5500
3.	Build twelve improved devices.	6000
4.	Take performance and life data on two devices and write short report.	3500
TOTAL		$20000

Deliverable items are ten improved devices, all optimization
and life test data, any additional test devices still operable,
and a short report. These items will be delivered within six
months of receipt of order.

PROGRAM PERSONNEL

The program manager for this effort will be Dr. James Shaw.
His eight years of experience in flashlamp behavior studies and
ceramic device design make him well qualified for the job. Mr.
John Turner will be responsible for device fabrication efforts.
Laboratory radiometric measurements and optimization studies will
be performed by Mr. Robert Maynard.

In addition, ILC has extensive flashlamp and ceramic to metal
sealing expertise on which to draw. Dr. Paul Lovoi has been in-
strumental in developing short pulse UV producing flashlamps for
specialized laser pumping applications and will be available to
the program as a consultant. If required, Dr. Leonard Reed will
also be available as a consultant on ceramic to metal sealing
technology. Biographies of these people follow.

RELATED EXPERIENCE

The following list of contracts performed by ILC illustrates
the depth and breadth of ILC experience in the field of lamp design.
Also included to show our capabilities in ceramic to metal devices
are ILC Bulletins 202 and 1705 and an ILC Company Profile.

DR. JAMES F. SHAW, SECTION MANAGER

EXPERIENCE:

1976 - Present	ILC TECHNOLOGY, INC., Sunnyvale, California Head of Optical Sources Section. Responsible for development activities related to military and commercial optical sources. Principal areas of activity are efficient laser pump sources, countermeasure lamps, very short pulse flashlamps and alkali metal lamps.

1968 - 1976   XEROX ELECTRO-OPTICAL SYSTEMS, Pasadena, California

1972 - 1976   Manager of Xerox Light Source Technology Program and Manager of Device Engineering Section. Responsible for evaluation and development of all incoherent light sources intended for advanced Xerox copiers. Main development area were pulsed xenon flashlamps for fusing applications, low pressure sodium lamps for exposure sources, and super high pressure short arcs for scanning sources.

1970 - 1972   Responsible for the development and performance characterization of special purpose light sources for federal programs. Primary emphasis was on pulsed cesium lamps and their output between 0.4 and 5.0 μm.

1968 - 1970   Responsible for the interpretation of data from optically augmented reconaissance systems. Performed analysis of thermal, mechanical, and radiative problems related to alkali metal lamp development.

1964 - 1968   STANFORD UNIVERSITY, Palo Alto, California. Graduate Research Assistant performing research in the field of MHD energy conversion. Primary emphasis was on closed cycle seeded noble gas systems.

EDUCATION:

1959 - 1963   California Institute of Technology, B.S. (with honors) in Engineering

1963 - 1968   Stanford University, M.S. in Mechanical Engineering, Ph.D. in Mechanical Engineering

PUBLICATIONS & PATENTS:

Coauthor of five journal articles and five technical articles in the field of plasma physics and plasma devices. One patent pending on the design of low pressure sodium lamp systems.

EXPERIENCE:

April 1975 to Present   ILC Technology, Inc., Sunnyvale, California.
                         Responsible for the design and development of
                         special lamp products.

1972-1975   U.S. Scientific Instruments, Inc., Boston, Mas-
                         sachusetts. Organized the Flashlamp Department.
                         Hired and trained engineers, technicians, and
                         assemblers. Introduced assembly techniques and
                         instituted continuing cost reduction.

1955-1972   EG&G, Inc., Boston, Massachusetts. General
                         Manager. Profit-and-loss responsibility for the
                         High Energy Switch Operation and the Flash Sources
                         Operation. Directed the design, development, and
                         production of electronic components, with particular
                         emphasis on the following electron tubes: Flashlamps,
                         Thyratrons, Spark Gaps, and Cathode-Ray Tubes.
                         Each of these devices was state-of-the-art in its
                         own class. Many technical innovations and inven-
                         tions were made under his leadership.

1949-1955   Raytheon Company, Waltham, Massachusetts.
                         Senior Engineer. Directed a small group of develop-
                         ment engineers. Developed several magnetrons.
                         Introduced a new method of development which
                         significantly reduced development time and cost.

EDUCATION:

1970   Master of Business Administration, Boston University.
1953   Master of Arts in Physics, Boston University.
1949   Bachelor of Electrical Engineering, Rensselaer
                         Polytechnic Institute.

PATENTS:

                         U.S. Patents issued (to individual inventor and to
                         co-inventors):
                         #2,814,761 Electro-Mechanical Tuning of a C.W.
                                    Magnetron.
                         #2,847,613 Apparatus for Displacing Magnetron
                                    Tuner Resonances.
                         #2,869,032 Method of and Apparatus for the Reduction
                                    of Thermionic Emission in Discharge Devices.
                         #3,350,602 Gaseous-Discharge Device Having a Trigger
                                    Electrode and a Light Producing Spark Gap to
                                    Facilitate Breakdown Between the Trigger
                                    Electrode and One of the Principal Electrodes.
                         #3,356,888 Two-Electrode Spark Gap with Interposed
                                    Insulator.
                         #3,399,147 Gas Mixture for Electric Flashtubes.

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ROBERT L. MAYNARD, DEVELOPMENTAL ENGINEER

EXPERIENCE:

August 1969 - Present	ILC TECHNOLOGY, INC., Sunnyvale, California. Supervisor, Optics Laboratory. Responsible for electro-optical testing on new and existing radiation sources. Responsible for laser optics quality assurance. Set up optical test facility. Project Engineer on PEM program for laser pumps. Performed extensive tests on optimizing lamp behavior for various laser applications.
1968 - 1969	UNITED TECHNOLOGY CENTER, Division of United Aircraft Corporation, Sunnyvale, California. Conducted developmental tests on advanced solid fuel rocket steering mechanism. Instrumented hybrid rocket motor test bay and assisted in developmental testing of new motor.
1964 - 1968	INSTITUTE OF SCIENCE AND TECHNOLOGY, UNIVERSITY OF MICHIGAN, Ann Arbor, Michigan. Assistant in Research. Responsible for reduction of acoustic and seismic data from propogation and detection studies.

EDUCATION:

1964	Bachelor of Arts in Physics, Western Michigan University, Kalamazoo, Michigan.

PAUL A. LOVOI, MANAGER OF RESEARCH

EXPERIENCE:

February 1974 to Present

ILC TECHNOLOGY, INC., Sunnyvale, California
Manager of Research and Large Laser Components
Group. Present work includes program manage-
ment of the large laser components group and
responsibility for the Rutherford Laboratory and
Osaka University laser amplifier systems.
Responsibility for large laser systems design and
new component development and testing. Previous
work includes at ILC, theoretical flashlamp elec-
trical and optical modeling, advanced flashlamp
design and laser research, plasma diagnostics
studies.

May 1972 - Jan. 1974

LOS ALAMOS SCIENTIFIC LABORATORY, Los Alamos,
New Mexico, Physics Group. Ph.D. disserta-
tion work in low energy nuclear physics as well
as work in pulsed Nd:Glass, high power pulsed
tuneable dye lasers, laser fusion target pellet
evaluation and laser isotope separation.

EDUCATION:

1969

Bachelor of Science in Physics
Bachelor of Science in Mathematics
Pacific University

1971

Masters of Science in Physics
University of New Mexico

1974

Doctor of Philosophy in Physics
University of New Mexico at Los Alamos

DR. LEONARD REED, VICE PRESIDENT, ENGINEERING

EXPERIENCE:

March 1970 - Present	**ILC TECHNOLOGY, INC.**, Sunnyvale, California Company-wide responsibility for Contract Engineering and for in-house development programs. Together with the President of ILC, decides on new product areas for ILC and new areas in which to carry out contract research. Significant programs that are currently being managed at ILC include Space Shuttle lighting, Communications Satellite Optical Sources and Laser Components for Nuclear Fusion.
March 1969 - March 1970	**ILC LABORATORIES.** Director
1960 - March 1969	**EIMAC, DIVISION OF VARIAN ASSOCIATES**, San Carlos, California 1965 - 1970 Manager, Advanced Products Operation. Directed product and device development in the areas of energy conversion, microwave/plasma chemical procession and electro-optics, concentrating on arc lamps, gas laser, and special electron tubes. Served on the Varian Merger and Acquisition Committee and charted the formation of the Light Sensing and Emission Division (LSE). Served as a member of the Varian solid state task force. Arranged for the spin-off of the Eimac Laser Department to form Laser Sciences, Inc 1963 - 1965 Manager, Research and Special Engineering Department. Directed work on liquid metal corrosion and materials development for aerospace and electronic use. 1960 - 1963 Group Leader, Electron Tube Techniques Department. Also lectured on industrial program basis at Stanford University.
1957 - 1960	**KAISER CHEMICAL LABORATORIES**, San Jose, California In charge of Research and Product Development.
1955 - 1957	**ROYAL AIR FORCE**, Britain. Set up and serviced radar and associated electronic equipment.
1953	**OHIO STATE AND RUTGERS UNIVERSITY.** Fullbright Fellowship. Lectured and carried out research work on the electrical properties of materials.

EDUCATION:

Bachelor of Science (honors) Chemistry and Metallurgy, University of Wales, 1950. D.I.C. in Ceramics, Ph. D. in Applied Physical Chemistry, Imperial College, London, 1952.

Post-Doctorate courses, Material and Quantum Electronics (University of California, Berkeley), Optics (UCLA), Electronics (RAF), General Management.

PUBLICATIONS AND PATENTS:

Twenty-four papers and ten patents issued or pending in the field of electronic materials and devices.

ILC TECHNOLOGY

SELECTED LISTING OF ILC DEVELOPMENT CONTRACTS

Title	Sponsoring Agent	Contract Number	Cost
Optical Pumps for Lasers (alkali metal)	USAECOM	DAAB07-70-C-0035	$ 75,135
Optical Pumps for Erbium Lasers (pulsed alkali metal)	USAECOM	DAAB07-70-C-0296	$ 86,900
Flash Beacon Systems (helical lamp)	USCG	DOT-CG-90, 544A	$ 64,005
High Intensity Flash Beacon System (linear lamp)	General Dynamics, Convair Division	P.O. 71-02285	$ 750
Collimated Light Source and Power Supply	USAF Cambridge	F19650-70-C-0604	$ 8,173
Searchlight System 2500 W	USAF Cambridge	F19650-70-C-0413 DO 2341	$ 4,990
Prototype Underwater Lighting System	Naval Undersea R&D Center, Pasadena	N66001-70-C-0906	$ 3,242
Investigations of Possible Causes for Deterioration Iodide Doped Mercury Short Arc Lamp	Naval Undersea R&D Center, Pasadena	N66001-69-2511	$ 950
Alkali Metal Lamps (thermal mechanical studies)	NAVAIR	AIR-360-69-18	N/C
Alkali Metal Vapor Lamps	Dept. of the Army Fort Belvoir	DAAK02-71-C-0199	$ 40,000

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Title	Agency	Contract Number	Amount
Long Life Krypton Arc Lamp	WPAFB	F33615-71-C-1645	$ 49,939
Alkali Metal Laser Pump Lamps for Space Nd:YAG Lasers	WPAFB	F33615-71-C-1812	$ 75,000
Thallium-Mercury-Xe Lamps	NURDC	N66001-71-C-0703	$ 20,000
Exploration of New Technology for High Power Alkali Metal Lamps	NRL, Arlington	N00014-71-C-0384	$ 40,000
Alkali Vapor Lamps	ONR	N00014-71-C-0183	$ 60,000
Reliable Optical Pumps for Lasers	ECOM	DAAB07-71-C-0239	$ 90,000
Pump Lamps for Nd:YAG Lasers	WPAFB	F33615-71-Q-1949	$ 99,000
Ultraviolet Output from Laser Pumps	Hughes, Culver City	P.O. 04-408582-F54	$ 9,000
Alkali Vapor Lamps	WPAFB	F33615-72-C-1694	$ 34,989
In-Pavement and Above Ground Flashing Lights (ILC is major subcontractor for all flash-lamps and power supply assemblies)	FAA	FA71WA-2557	$ 60,000
Optical Pumps for Holmium Lasers	USAECOM	DAAB07-72-C-0274	$ 84,139
Development of a Special Purpose Flashlamp	U.S. Army Harry Diamond Labs	DAAG-39-73-C-0045	$ 58,660
High Efficiency Far Infrared Radiation Source	USAECOM NVL	DAAK02-73-C-0032	$ 44,192
Manufacturing Methods Program for Alkali Metal Lamps	WPAFB	F33615-72-1735	$366,125

Design, Develop & Fabricate 250 Watt Doped Short Arc Lamps	NURDC	N66001-72-C-0566	$ 19,959
Disc Laser Amplifier	NRL	N00014-73-C-0142	$ 24,625
Doped Flashlamps	NELC	N00123-73-C-1148	$ 90,608
Production Engineering Methods, Program for Optical Pumps	USAECOM	DAAB05-73-C-2078	$ 90,608
Analytical & Experimental Studies of High Energy Helical Flashlamps	U. of California Los Alamos	LP3-17043-1	$ 16,896
Design Study for Glass Seals	Martin	RC-140175	$ 16,267
K-Rb Laser Pump Lamp	WPAFB	F33615-74-C-1027	$ 111,907
Rb Lamps for Engineering Feasibility Model	Sylvania	SD 01218 SD 01741	$ 119,996 28,766
27 mm Bore Flashlamps for Laser Amplifier	U. of California Lawrence Livermore	PO 3043805	$ 1,435
1 kW Short Arc Evaluation	USANVL Fort Belvoir	DAAK02--74-C-0020	$ 25,000
Xenon F/L for High Energy Application	U. of California Lawrence Livermore	PO 3024405 & PO 3024505	$ 19,000
Xenon Lamps for Viking Biological Lander	TRW Systems	047DF1-S	$ 148,000
Space Shuttle Interior Lighting	NASA, subcontract Rockwell	P.O. M352XMN-483076	$1,200,000
K-Rb Arc Lamp Ni End Cap Reliability Investigations	MDAC-E	P.O. Y4E655	$ 60,000

Laser Pump Lamp	WPAFB	F33615-75-C-1080	$ 99,000
Iodine Photodissociation Laser Pump Study	Sandia Lab	P.O. 67-9724	$ 8,000
Dye Laser Pump Lamp Optimization	U. of California Los Alamos	P.O. 4705291	$ 11,000
Study of Lifetime Characteristics of Large Diameter (19 mm Bore) Flashlamps	U. of California Lawrence, Livermore	P.O. 4316805	$ 17,466
Life Characteristics of Flashlamps With Converted and Unconverted Cerium-Doped Fused Quartz Envelopes	U. of California Lawrence, Livermore	P.O. 4076305	$ 2,350
Arc Growth Studies	U. of California Lawrence, Livermore	P.O. 5707605	$ 4,395
Flashlamp Wall Examination During 10,000 Shot Tests	U. of California Lawrence, Livermore	P.O. 5287705	$ 20,100
Flashlamp Infant Mortality Study	U. of California Lawrence, Livermore	P.O. 8954605	$ 19,500

Date	Project	Organization	Contract Number	Amount
1-6-76	Metal Additive Flashlamp Development	ERDA-Sandia	E(04-3)-1149	$ 43,047
2-11-76	DISC Laser Amplifiers	Rutherford Laboratory England	NIC28466RL	$521,340
3-12-76	K-Rb Lamp Development	U.S. Air Force-SAMSO	F33615-76-C-1029	$598,500
3-76	K-Rb Arc Lamp-Phase I	MDAC-E	PO Y5E191	$698,000
6-2-76	I R Lamp Improvement for the AN/ALQ123	U.S. Navy-PMR	N00019-76-C-0449	$ 94,075
6-7-76	Pulsed Light Source	U.S. Army Missile Command	DAAA01-76-C-0916	$ 40,000
8-18-76	Coaxial Dye Laser Pump Lamp Tests	U.S. Navy-NELC	N00953-76-M-A247	$ 9,985
8-27-76	Metal Additive Short Arc Lamp Development	Eastman Kodak Co.	60-2876-91123	$ 35,669

CERAMIC/METAL PRODUCTS

Saphire Windows · Moly Cup Seals

Ceramic/metal assemblies withstand:

- High Temperature
- Low Temperature
- Thermal Shock

- Nuclear Radiation
- Abrasion
- High Voltage

- Corrosive Environments
- High Vacuum and Pressure
- Physical Stress
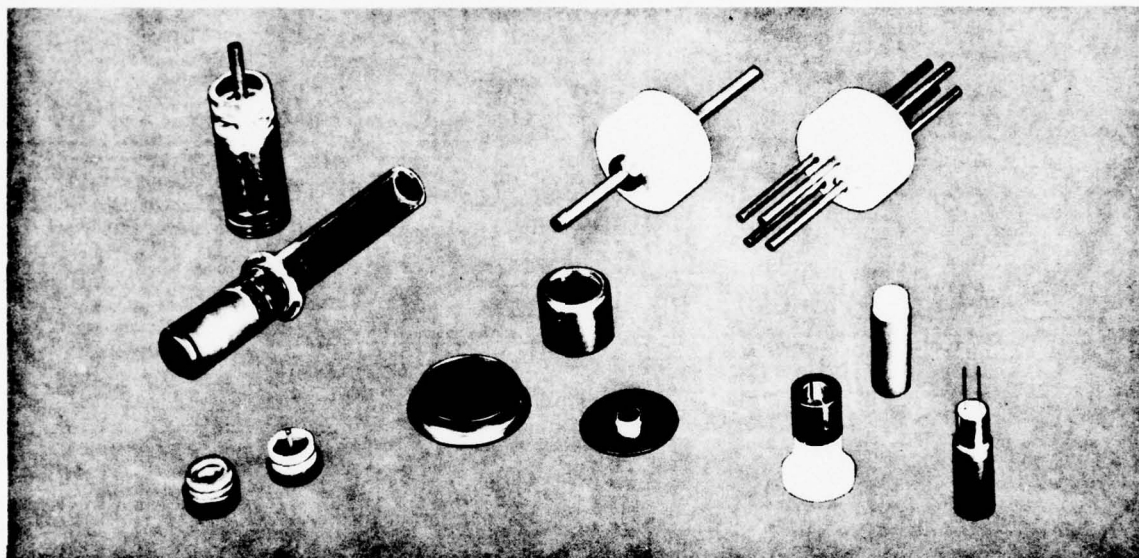
Applications

Vacuum Feedthroughs
Probes
High Voltage Terminal Bushings
Nuclear Reactor Components
High Voltage Test Equipment
Semiconductor Headers
Explosion-Proof Assemblies
Variable Pressure Transducers
Cryogenic Devices
Thermionic Converters
Exploding Wire Detonators
Gas Laser Cavities
Nuclear Batteries
Flashlamps and Arc Lamps
Alkali Vapor Lamps
Resistance Thermometers
Standoff Insulators
Spark Gaps
High Power Heat Sinks
Optical Windows
Viewing Ports
Moly Cup Seals
And Many More

Ceramic/metal assemblies possess a unique combination of desirable electro-mechanical, thermal, chemical, and optical characteristics, some of which are listed above. The advances in material processing make it practical to utilize these superior components in new equipment and system designs.

The ILC Materials Technology Department is staffed with an industry-recognized scientific and production team whose members have published over 30 papers and hold 26 patents involving materials and ceramics. At ILC we have a complete in-house capability for cleaning, coating, and plating most metals, ceramics, and glasses. We have furnaces for metallizing ceramics, including beryllia, alumina, and sapphire. Other furnaces are used for hydrogen brazing and vacuum brazing to 2200°C.

We have an all dry, all metal processing station capable of 500°C bake-out and vacuum of 10^{-9} Torr, with provision for gas refill to 30 atmospheres. A wide choice of metallizing and brazing techniques is employed to obtain the best results for the intended application, and with the lowest cost. Electron beam and TIG welding are also routinely used, X-ray, electron microscope, metallographic, and microprobe analytical techniques are employed. Our Quality Control procedures conform to MIL-SPEC and NASA standards. All ceramic/metal seals and brazed metal parts are routinely tested for helium leak rates on a mass spectrometer.

In addition to conventional metallizing, we can also coat ceramics, metals, and single crystal materials with highly adherent silver and copper metal coatings applied at room temperatures using ion implantation techniques. These high reflectivity, high bond strength, vacuum tight coatings can be brazed or soldered to other materials. For example, Nd-Yag laser rods have been joined to copper heat conduction sinks. The inner coating surface on the rod, with its high reflectivity, retains the pumping light inside the laser cavity.
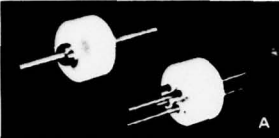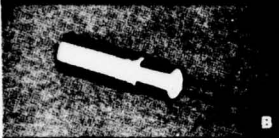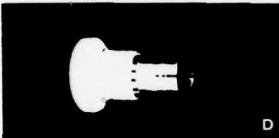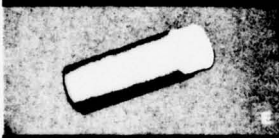
Successful solutions to difficult sealing problems, involving operation under stringent operating conditions, have been especially satisfying to us. But we welcome your parts drawings or problems whether routine or exotic.

The reverse side shows some typical assemblies that are standard designs or that we have fabricated for others. Can we help you also? Please call or write for a prompt reply, a quotation, or a recommendation.

	Application	Materials	Operating Requirements	Brazing Technique
A	High voltage feedthrough	High purity alumina to beryllium-copper or kovar	10,000 psi hydro-static pressure with 20 year reliability	Moly-manganese metallizing and copper or copper-silver braze
B	High temperature thermocouple feedthrough for nuclear reactor	High purity alumina to kovar and stainless steel, Tungsten rhenium leads	Vacuum and inert gas, for 600°C operation	Moly-manganese metallizing and copper braze
	Moly cup seals for lamps and gas lasers	Molybdenum to quartz; also molyb-denum to kovar and other metals	High pressure 300 psi inert gas and air	Moly to metal transitions use copper and copper-silver brazes
D	Heat sink for short-arc high intensity xenon lamp	Beryllia to copper	To 300°C in air for 10,000 hours or 500°C for 500 hours	Moly-manganese metallizing and copper-silver braze
	Sensor sheath for nuclear reactor or turbogenerator	Alumina to kovar	3,000 psi pressure and 400°C	Moly-manganese metallizing and copper braze
F	Thermionic converter for heart pacer	99.99 alumina to columbium alloy	High temperature alkali metal to 1200°C	Zirconium - vanadium - columbium active alloy
	Sapphire windows for vacuum and pressure vessels, UV or IR windows, cryogenic dewers, etc.	Sapphire or Lucalox window to kovar cup or flange	To 600°C in air, Liquid He temperature, to 3500 psi pressure	Moly-manganese metallizing and copper braze
	Radiance standard with incandescent ribbon	Sapphire, alumina, and kovar, with tungsten ribbon, inert gas fill	Transmission to 5 microns	Moly-manganese metallizing and copper braze
I	Alkali-metal vapor containment vessel	Alpha-alumina to stainless steel	Sodium vapor, 300°	Multi-layer evapo-rated metallizing and copper braze
J	Heat sink for Nd-Yag laser rod, conductively cooled from vacuum environment	Nd-Yag crystal and copper	−15°C in vacuum, 99% reflective highly adherent metallized coating	Ion implanted silver coating brazed to copper heat sink
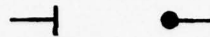
ILC Technology
164 Commercial Street ● Sunnyvale, California 94086

Sapphire Window Assemblies

ASSEMBLY DESCRIPTION

ILC standard sapphire window assemblies (depicted below) are constructed by joining sapphire windows to Kovar flanges, sleeves or cups (series S-2, S-3, and S-4, respectively) using moly-manganese metallizing and brazing. The Kovar terminations may be joined to mating metal members by high temperature brazing methods (to 1040°C) or by heliarc welding. Available sizes are shown in the table below. Custom fabricated window assemblies employing customer-specified terminations can also be provided.

S-2 SERIES
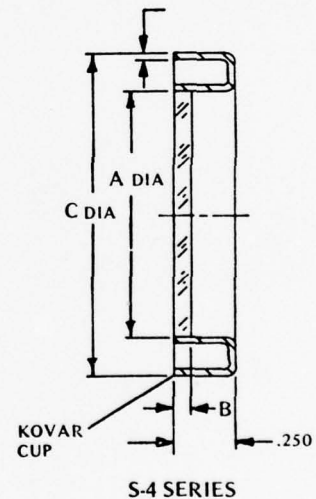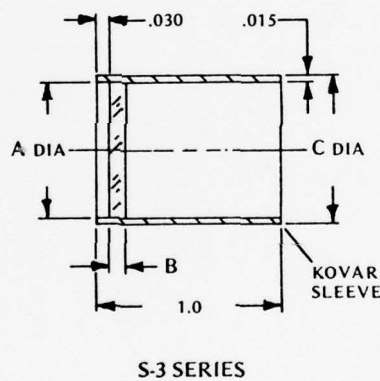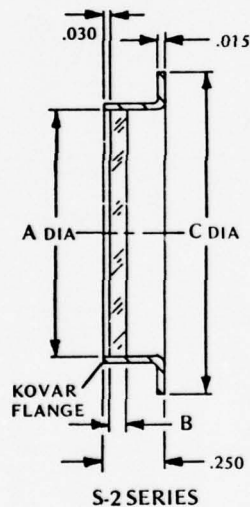
S-3 SERIES

S-4 SERIES

STANDARD SAPPHIRE WINDOW ASSEMBLIES

(Dimensions in inches, tolerances xxx dec ± 0.005, xx dec ± 0.010)

SERIES	SIZE	A	B	C
S-2	-3	0.565	0.060	1.000
S-2	-4	0.730	0.070	1.250
S-2	-5	1.064	0.090	1.500
S-3	-1	0.234	0.060	0.264
S-3	-3	0.565	0.060	0.595
S-3	-4	0.730	0.070	0.760
S-3	-5	1.064	0.090	1.094
S-4	-3	0.565	0.060	0.820
S-4	-5	1.064	0.090	1.242

TYPICAL APPLICATIONS

- Detector windows for UV and IR devices
- Windows for vacuum and pressure vessels
- Optical parts for high temperature atmosphere furnaces
- Windows for low temperature applications
- For opto-electronic devices
- For plasma devices
- Probes for corrosive environments
- Hardened radiation resistant packages for space applications
- Thermionic converter assemblies

SAPPHIRE METAL ASSEMBLY PROPERTIES

Optical transmission of sapphire is much superior to fused quartz in the UV and IR regions. Typical transmission values for a 0.040 inch thick window are:

Wavelength (nm)	150	200	300	3000	6000
Transmission %					
Regular Sapphire	21	66	80	92	40
UV Grade Sapphire	70	80	85	92	40

An additional transmission loss of less than 3% is encountered when the window is heated to 430°C; transmission in the IR region is generally useful up to 1500°C.

Standard tolerance on part dimensions is ± .010 inch for two decimal places, and ± .005 inch for three decimal places but much closer tolerances are held on piece parts. For example, standard tolerance on windows is flat and parallel to .001 inch with a window glass finish and a ± .003 inch tolerance in diameter.

Thermal shock resistance is excellent. Windows will withstand repeated cycling in air from liquid nitrogen temperature to 600°C.

Mechanical stress rating is 1000 g's 1 msec (minimum) for mechanical shock, 50 g's, 20-3000 cps for vibration sinusoidal stress.

Sapphire-Kovar joint integrity involves a seal strength greater than 10,000 psi average and a leak rate less than 1×10^{-8} std. cc helium/sec.

CUSTOM SAPPHIRE METAL ASSEMBLIES

A variety of geometries are feasible including window discs up to three inches in diameter and window cylinders up to two inches in diameter and four inches long. Many custom terminations are possible including stainless steel, copper high vacuum flanges and TO-5 can headers.

For severe environments, braze systems are available that can extend service in vacuum to 1600°C, in air to 1200°C, in alkali metal environments to 1000°C and in halogen atmospheres to 800°C.

Window assemblies can be fabricated into more complex geometries (e.g., alkali metal test cells).

Consultation with ILC engineers is recommended before submitting detailed drawings for custom quoting: we can often suggest engineering approaches that will simplify your design problems.

SAPPHIRE CHARACTERISTICS

Sapphire possesses a hexagonal crystal structure and undergoes no phase changes up to its melting point of 2040°C. It is chemically stable in many corrosive environments. Sapphire has zero porosity and exhibits a minimum of outgassing in vacuum. Other physical and electrical properties are as follows:

Hardness (Moh's scale)	9 (diamond 10)
Tensile strength 20°C-1000°C	20,000 psi
Compressive strength 20°C-1000°C	200,000 psi
Thermal expansion 20°C-1000°C	7.7×10^{-6} cm/cm
Thermal conductivity 20°C-1000°C	0.08-0.016 cal/cm^2/sec/°C/cm
Electrical strength	480,000 V/cm
Dielectric constant at 3000 MHz (av.)	9.6
Loss tangent	0.0001

ILC TECHNOLOGY GENERAL CAPABILITY

Other transparent, translucent and opaque ceramic to metal assemblies are manufactured.

Other joining methods include hydrogen atmospheric brazing with copper, copper-gold, copper-silver; active metal alloy vacuum brazing from 200°C-1800°C; and ceramic brazing from 400°C-1500°C.

ILC specializes in the fabrication of complex devices requiring specialized optical and electronic capability. Technical Bulletin No. 3, "Ceramic to Metal Sealing" and Bulletin 202, "Ceramic/Metal Products" are available on request.

ILC is a leading manufacturer of optical sources and equipment. An ILC "Profile" is available on request.

Information furnished is believed to be accurate and reliable, however, no responsibility is assumed for the use.

ATTACHMENT E

ILC WORK STATEMENT

The contractor shall make available the technical personnel needed to conduct the proposed program together with all the necessary related services, facilities, supplies and materials. The scope of the program is to fabricate VUV light sources of the general type depicted in Figure 1, with electrode geometry and electrode-window orientation and geometry varied as required for optimization. Source parameters will be optimized for maximum energy flux in the 145 nm to 165 nm spectral band. Ignition tests on a stationary, stoichiometric ratio mixture of hydrogen and oxygen at about 300 torr pressure will be employed as the optimization criterion. Input energy of at least 0.5 J to 50 J is required with output pulse width of 100 μs or less. (Output energy is expected to be in the range of 0.05 mJ to 5 mJ). Light source radiant output reproducibility of $\pm15\%$ and lifetime of 10^3 shots or greater is required. Light source window is to be of certified UV grade sapphire material. Lamp pressure is expected to be approximately 3 atmospheres (cold) of xenon gas, although other pressures or gases can be used as needed for optimization.

At least eight devices of varying design will be fabricated, filled and tested sequentially. When a satisfactory VUV source has been identified, two will be life tested. The original design can be modified based on life test and optimization test results. Following this, twelve improved devices will be fabricated and two tested for performance and life.

A small power supply will be constructed once the electrical characteristics of the device are identified. It will use an ILC rate generator (RG10), pulse generator (PG10), trigger transformer (T105) for trigger electronics, and a universal voltronics power supply for charging the main capacitor. The power supply will be deliverable.

DELIVERABLES, SCHEDULE, AND COST

Deliverable items are: (1) ten improved devices, (2) the power supply, (3) all optimization and life test data, (4) any additional test devices still operable, and (5) a final report. These items will be delivered within six months for receipt of order. Total cost is not to exceed $21,000.
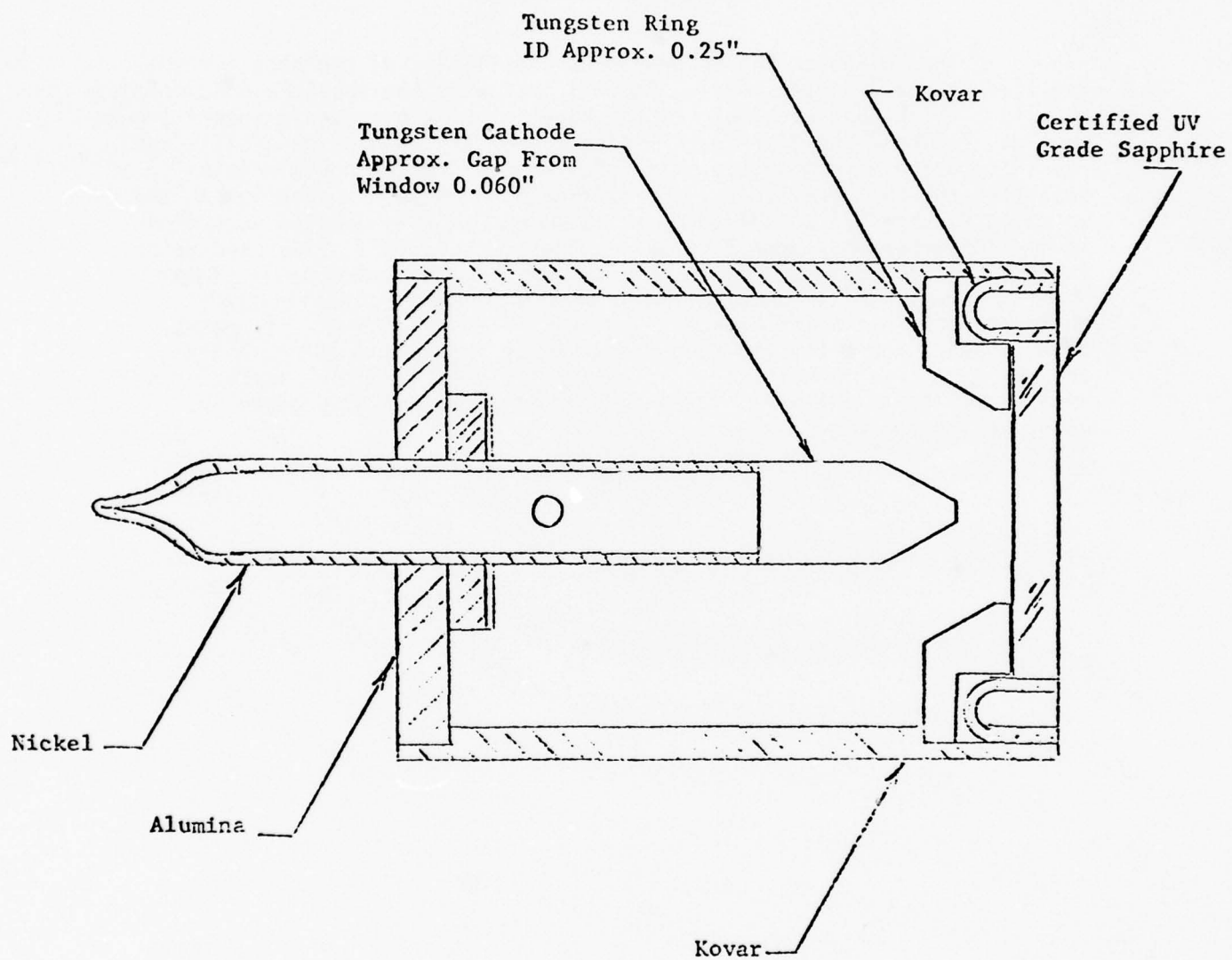
Figure 1 - VUV Light Source Preliminary Configuration

APPENDIX II

COMPILATION OF MODEL DATA

The following tables provide a compilation of the data currently utilized in the computer model. Table 1 indicates the possible photochemical reactions which can contribute to the kinetics of a hydrogen/oxygen/nitrogen system. Tables 2 and 3 presents the complimentary absorption coefficients and information on window transmission. The absorption coefficients represent the best available literature values. Oxygen absorption in the wavelength range 175 to 204 nm (Schumann-Runge band) is modeled according to a sixth order polynominal fit according to Kockarts*. Tabulated values in this region are simple average values to indicate trend only. Table 4 lists a total of 89 reactions which are included in modeling the photochemical initiation kinetics and heat release. The kinetic rates were selected for a limited temperature range from about 298 K to 1000 K and are expressed in units of s^{-1}, cm^3/particle$^{-1}s^{-1}$, or cm^6/particle$^{-2}s^{-1}$ with temperature in Kelvin. Heat of combustion at 298 K is given in units of kcal/mole.

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*Kockarts, G., "Absorption and Photodissociation in the Schumann-Runge Bands of Molecular Oxygen in the Terrestrial Atmosphere", Planet. Space Sci., Vol. 24, pp. 589-604, 1976.

TABLE 1

PHOTODISSOCIATION REACTIONS WHICH CAN OCCUR DURING PHOTOCHEMICAL COMBUSTION INITIATION OF HYDROGEN/OXYGEN/NITROGEN MIXTURES

Reaction	Wavelength Region (nm)
$O_2 + h\nu \rightarrow O + O$	175 - 245
$O_2 + h\nu \rightarrow O + O(^1D)$	134 - 175
$O_3 + h\nu \rightarrow O_2 + O$	> 310
$O_3 + h\nu \rightarrow O_2(^1\Delta_g) + O(^1D)$	260 - 310
$O_3 + h\nu \rightarrow O_2(^1\Sigma_g^+) + O(^1D)$	< 260
$H_2O + h\nu \rightarrow OH + H$	< 242
$HO_2 + h\nu \rightarrow OH + O$	< 456
$H_2O_2 + h\nu \rightarrow OH + OH$	< 365

TABLE 2

VUV AND UV ABSORPTION COEFFICIENTS OF VARIOUS SPECIES OF INTEREST (AVERAGE VALUES EVERY 1 nm)

Wavelength (nm)	Absorption Coefficient of Indicated Species (cm^{-1})				
	O_3	H_2O_2	HO_2	O_2	H_2O
140	1.90E+02	1.52E+02	2.87E+01	3.80E+02	1.70E+01
141	1.75E+02	1.48E+02	3.03E+01	3.96E+02	1.80E+01
142	1.62E+02	1.30E+02	3.19E+01	3.97E+02	1.33E+01
143	1.50E+02	1.18E+02	3.35E+01	3.95E+02	1.31E+01
144	1.42E+02	1.11E+02	3.51E+01	3.90E+02	1.36E+01
145	1.34E+02	1.09E+02	3.67E+01	3.75E+02	1.41E+01
146	1.27E+02	9.90E+01	3.83E+01	3.55E+02	1.73E+01
147	1.20E+02	1.04E+02	3.98E+01	3.44E+02	1.99E+01
148	1.11E+02	1.00E+02	4.14E+01	3.30E+02	2.25E+01
149	1.03E+02	9.60E+01	4.30E+01	3.08E+02	2.64E+01
150	9.20E+01	9.40E+01	4.46E+01	2.90E+02	3.20E+01
151	8.20E+01	9.00E+01	4.62E+01	2.77E+02	3.70E+01
152	6.94E+01	8.80E+01	4.78E+01	2.60E+02	4.25E+01
153	6.32E+01	9.10E+01	4.94E+01	2.40E+02	4.80E+01
154	5.70E+01	9.20E+01	5.10E+01	2.18E+02	5.50E+01
155	5.25E+01	9.10E+01	5.25E+01	2.00E+02	6.10E+01
156	4.85E+01	8.90E+01	5.41E+01	1.82E+02	6.80E+01
157	4.35E+01	9.00E+01	5.57E+01	1.67E+02	7.50E+01
158	3.90E+01	9.60E+01	5.73E+01	1.51E+02	8.25E+01
159	3.45E+01	1.01E+02	5.89E+01	1.35E+02	9.10E+01
160	2.93E+01	1.02E+02	6.05E+01	1.22E+02	9.90E+01
161	2.78E+01	1.08E+02	6.21E+01	1.07E+02	1.05E+02
162	2.62E+01	1.09E+02	6.37E+01	9.30E+01	1.11E+02
163	2.42E+01	1.08E+02	6.52E+01	7.90E+01	1.18E+02
164	2.29E+01	1.07E+02	6.68E+01	6.50E+01	1.23E+02
165	2.28E+01	1.06E+02	6.84E+01	5.50E+01	1.27E+02
166	2.28E+01	1.02E+02	7.00E+01	4.50E+01	1.22E+02
167	2.28E+01	9.85E+01	7.16E+01	3.60E+01	1.21E+02
168	2.28E+01	9.45E+01	7.32E+01	3.00E+01	1.17E+02
169	2.28E+01	9.15E+01	7.48E+01	2.50E+01	1.14E+02
170	2.28E+01	8.65E+01	7.64E+01	2.04E+01	1.10E+02
171	2.28E+01	8.00E+01	7.80E+01	1.72E+01	1.05E+02
172	2.28E+01	7.30E+01	7.95E+01	1.41E+01	9.50E+01
173	2.28E+01	6.50E+01	8.11E+01	1.11E+01	8.50E+01
174	2.26E+01	5.62E+01	8.27E+01	8.50E+00	7.40E+01
175	2.22E+01	5.10E+01	8.43E+01	3.00E+00	6.80E+01
176	2.20E+01	4.70E+01	8.59E+01	1.00E+00	5.80E+01
177	2.18E+01	4.41E+01	8.75E+01	5.20E-01	4.90E+01
178	2.13E+01	4.01E+01	8.91E+01	3.50E-01	3.90E+01
179	2.08E+01	3.72E+01	9.07E+01	1.82E-01	2.60E+01
180	2.02E+01	3.48E+01	9.22E+01	1.13E-01	1.62E+01
181	1.98E+01	3.25E+01	9.38E+01	7.20E-02	9.61E+00
182	1.91E+01	3.03E+01	9.54E+01	4.80E-02	5.71E+00
183	1.82E+01	2.84E+01	9.70E+01	3.10E-02	3.39E+00
184	1.77E+01	2.69E+01	9.86E+01	2.02E-02	2.01E+00

TABLE 2 (Continued)

Absorption Coefficient of Indicated Species (cm^{-1})

Wavelength (nm)	O_3	H_2O_2	HO_2	O_2	H_2O
185	1.71E+01	2.52E+01	1.00E+02	1.33E-02	1.20E+00
186	1.67E+01	2.39E+01	1.02E+02	9.20E-03	7.11E-01
187	1.63E+01	2.27E+01	1.03E+02	6.20E-03	4.22E-01
188	1.54E+01	2.14E+01	1.05E+02	4.30E-03	2.51E-01
189	1.46E+01	2.03E+01	1.06E+02	2.90E-03	1.49E-01
190	1.37E+01	1.92E+01	1.08E+02	2.02E-03	8.85E-02
191	1.29E+01	1.84E+01	1.10E+02	1.50E-03	5.26E-02
192	1.20E+01	1.75E+01	1.11E+02	1.10E-03	3.12E-02
193	1.17E+01	1.69E+01	1.13E+02	8.90E-04	1.85E-02
194	1.11E+01	1.64E+01	1.14E+02	7.00E-04	1.10E-02
195	1.07E+01	1.60E+01	1.16E+02	5.80E-04	6.55E-03
196	1.01E+01	1.56E+01	1.18E+02	5.10E-04	3.89E-03
197	9.58E+00	1.52E+01	1.19E+02	4.50E-04	2.31E-03
198	9.12E+00	1.50E+01	1.20E+02	4.00E-04	1.37E-03
199	8.70E+00	1.47E+01	1.22E+02	3.50E-04	8.15E-04
200	8.30E+00	1.40E+01	1.23E+02	3.49E-04	4.84E-04
201	8.10E+00	1.36E+01	1.23E+02	3.40E-03	
202	8.17E+00	1.31E+01	1.24E+02	3.30E-04	
203	8.60E+00	1.27E+01	1.25E+02	3.21E-04	
204	9.19E+00	1.23E+01	1.25E+02	3.12E-04	
205	9.78E+00	1.19E+01	1.25E+02	3.03E-04	
206	1.03E+01	1.15E+01	1.25E+02	2.93E-04	
207	1.11E+01	1.11E+01	1.24E+02	2.83E-04	
208	1.22E+01	1.08E+01	1.23E+02	2.74E-04	
209	1.38E+01	1.04E+01	1.23E+02	2.64E-04	
210	1.52E+01	1.01E+01	1.22E+02	2.54E-04	
211	1.73E+01	9.80E+00	1.21E+02	2.45E-04	
212	1.94E+01	9.43E+00	1.19E+02	2.35E-04	
213	2.19E+01	9.34E+00	1.18E+02	2.35E-04	
214	2.47E+01	9.18E+00	1.16E+02	2.16E-04	
215	2.79E+01	8.99E+00	1.14E+02	2.06E-04	
216	3.12E+01	8.80E+00	1.11E+02	1.97E-04	
217	3.49E+01	8.54E+00	1.09E+02	1.88E-04	
218	3.92E+01	8.10E+00	1.07E+02	1.79E-04	
219	4.40E+01	7.74E+00	1.04E+02	1.70E-04	
220	4.98E+01	7.42E+00	1.02E+02	1.61E-04	
221	5.46E+01	7.14E+00	1.00E+02	1.53E-03	
222	6.06E+01	6.90E+00	9.60E+01	1.44E-04	
223	6.71E+01	6.70E+00	9.40E+01	1.35E-04	
224	7.35E+01	6.50E+00	9.00E+01	1.26E-04	
225	8.13E+01	6.30E+00	8.60E+01	1.19E-04	
226	8.89E+01	6.09E+00	8.20E+01	1.11E-04	
227	9.68E+01	5.90E+00	7.90E+01	1.04E-04	
228	1.06E+02	5.77E+00	7.60E+01	9.64E-05	
229	1.16E+02	5.60E+00	7.30E+01	8.86E-05	

TABLE 2 (Continued)

Wavelength (nm)	Absorption Coefficient of Indicated Species (cm^{-1})			
	O_3	H_2O_2	HO_2	O_2
230	1.24E+02	5.41E+00	6.70E+01	8.41E-05
231	1.33E+02	5.25E+00	6.30E+01	7.52E-05
232	1.43E+02	5.10E+00	5.90E+01	6.63E-05
233	1.52E+02	4.98E+00	5.60E+01	6.04E-05
234	1.62E+02	4.80E+00	5.20E+01	5.46E-05
235	1.73E+02	4.63E+00	4.80E+01	4.95E-05
236	1.84E+02	4.49E+00	4.50E+01	4.52E-05
237	1.94E+02	4.34E+00	4.30E+01	4.10E-05
238	2.01E+02	4.19E+00	4.00E+01	3.68E-05
239	2.11E+02	4.02E+00	3.70E+01	3.27E-05
240	2.22E+02	3.88E+00	3.50E+01	2.87E-05
241	2.31E+02	3.71E+00	3.30E+01	2.49E-05
242	2.40E+02	3.58E+00	3.10E+01	2.10E-05
243	2.51E+02	3.42E+00	2.90E+01	1.85E-05
244	2.59E+02	3.30E+00	2.70E+01	1.60E-05
245	2.69E+02	3.18E+00	2.50E+01	
246	2.74E+02	3.04E+00	2.40E+01	
247	2.83E+02	2.90E+00	2.20E+01	
248	2.86E+02	2.80E+00	2.10E+01	
249	2.95E+02	2.69E+00	1.90E+01	
250	2.95E+02	2.58E+00	1.80E+01	
251	3.01E+02	2.46E+00	1.70E+01	
252	3.01E+02	2.35E+00	1.60E+01	
253	3.06E+02	2.25E+00	1.50E+01	
254	3.01E+02	2.15E+00	1.40E+01	
255	3.09E+02	2.05E+00	1.30E+01	
256	2.95E+02	1.96E+00	1.20E+01	
257	2.99E+02	1.87E+00	1.20E+01	
258	3.03E+02	1.79E+00	1.10E+01	
259	2.93E+02	1.71E+00	1.00E+01	
260	2.94E+02	1.63E+00	9.60E+00	
261	2.81E+02	1.56E+00	9.00E+00	
262	2.81E+02	1.49E+00	8.40E+00	
263	2.62E+02	1.42E+00	7.90E+00	
264	2.68E+02	1.36E+00	7.40E+00	
265	2.55E+02	1.30E+00	6.90E+00	
266	2.43E+02	1.24E+00	6.50E+00	
267	2.37E+02	1.19E+00	6.10E+00	
268	2.22E+02	1.13E+00	5.70E+00	
269	2.18E+02	1.08E+00	5.30E+00	
270	2.02E+02	1.03E+00	5.00E+00	
271	1.94E+02	9.88E-01	4.70E+00	
272	1.81E+02	9.44E-01	4.40E+00	
273	1.69E+02	9.02E-01	4.10E+00	
274	1.59E+02	8.61E-01	3.80E+00	

TABLE 2 (Continued)

Wavelength (nm)	Absorption Coefficient of Indicated Species (cm^{-1})		
	O_2	H_2O_2	O_3
275	1.49E+02	8.23E-01	3.60E+00
276	1.37E+02	7.86E-01	3.40E+00
277	1.28E+02	7.51E-01	3.20E+00
278	1.18E+02	7.17E-01	3.00E+00
279	1.08E+02	6.85E-01	2.80E+00
280	9.74E+01	6.55E-01	2.60E+00
281	8.91E+01	6.25E-01	2.40E+00
282	8.28E+01	5.98E-01	2.30E+00
283	7.65E+01	5.71E-01	2.10E+00
284	6.80E+01	5.45E-01	2.00E+00
285	6.11E+01	5.21E-01	1.90E+00
286	5.86E+01	4.96E-01	1.80E+00
287	4.94E+01	4.75E-01	1.60E+00
288	4.31E+01	4.54E-01	1.50E+00
289	3.87E+01	4.34E-01	1.40E+00
290	3.43E+01	4.14E-01	1.40E+00
291	3.03E+01	3.96E-01	1.30E+00
292	2.72E+01	3.78E-01	1.20E+00
293	2.37E+01	3.61E-01	1.10E+00
294	2.09E+01	3.45E-01	1.00E+00
295	1.84E+01	3.30E-01	1.00E+00
296	1.61E+01	3.15E-01	9.00E-01
297	1.40E+01	3.01E-01	9.00E-01
298	1.22E+01	2.88E-01	8.00E-01
299	1.05E+01	2.75E-01	8.00E-01
300	3.18E+00	2.62E-01	7.00E-01
301	8.28E+00	2.51E-01	7.00E-01
302	7.25E+00	2.39E-01	6.00E-01
303	6.27E+00	2.29E-01	6.00E-01
304	5.55E+00	2.19E-01	5.00E-01
305	4.98E+00	2.09E-01	
306	4.40E+00	1.99E-01	
307	3.81E+00	1.91E-01	
308	3.31E+00	1.82E-01	
309	2.87E+00	1.74E-01	
310	2.52E+00	1.66E-01	
311	2.31E+00	1.59E-01	
312	1.92E+00	1.52E-01	
313	1.74E+00	1.45E-01	
314	1.44E+00	1.38E-01	
315	1.30E+00	1.32E-01	
316	1.11E+00	1.26E-01	
317	1.09E+00	1.21E-01	
318	8.06E-01	1.15E-01	
319	8.40E-01	1.10E-01	

TABLE 2 (Continued)

Absorption Coefficient of
Indicated Species (cm^{-1})

Wavelength (nm)	O_3	H_2O_2
320	6.65E-01	1.05E-01
321	5.91E-01	1.00E-01
322	5.79E-01	9.60E-02
323	3.73E-01	9.17E-02
324	4.50E-01	8.76E-02
325	3.43E-01	8.37E-02
326	2.39E-01	8.00E-02
327	3.10E-01	7.64E-02
328	2.38E-01	7.30E-02
329	1.48E-01	6.97E-02
330	1.98E-01	
331	1.80E-01	
332	1.07E-01	
333	1.28E-01	
334	1.16E-01	
335	5.85E-02	
336	7.52E-02	
337	1.01E-01	
338	4.33E-02	
339	4.53E-02	
340	4.74E-02	
341	2.37E-02	
342	2.44E-02	
343	3.08E-02	
344	2.50E-02	
345	1.82E-02	
346	1.41E-02	
347	2.00E-03	
348	7.97E-03	
349	1.07E-02	
350	7.60E-03	
351	8.80E-03	
352	7.04E-03	
353	5.65E-03	
354	3.15E-03	
355	2.04E-03	
356	2.22E-03	
357	3.06E-03	
358	2.04E-03	
359	1.39E-04	

TABLE 3

VUV AND UV WINDOW TRANSMISSION DATA
(AVERAGE VALUES EVERY 1 nm)

Wavelength (nm)	UV Grade Sapphire	STD Grade Sapphire	UV Grade Quartz
140	6.50E-02	1.50E-02	0.0
141	2.00E-01	4.80E-02	0.0
142	3.00E-01	8.00E-02	0.0
143	3.65E-01	1.10E-01	0.0
144	4.27E-01	1.34E-01	0.0
145	4.80E-01	1.60E-01	0.0
146	5.29E-01	1.85E-01	0.0
147	5.70E-01	2.05E-01	0.0
148	6.06E-01	2.24E-01	0.0
149	6.35E-01	2.40E-01	0.0
150	6.59E-01	2.51E-01	0.0
151	6.78E-01	2.67E-01	0.0
152	6.92E-01	2.79E-01	0.0
153	7.03E-01	2.90E-01	0.0
154	7.12E-01	3.02E-01	0.0
155	7.22E-01	3.15E-01	0.0
156	7.31E-01	3.27E-01	0.0
157	7.39E-01	3.39E-01	0.0
158	7.47E-01	3.50E-01	0.0
159	7.51E-01	3.61E-01	0.0
160	7.57E-01	3.70E-01	1.70E-01
161	7.60E-01	3.80E-01	4.14E-01
162	7.61E-01	3.90E-01	5.35E-01
163	7.63E-01	3.99E-01	6.20E-01
164	7.68E-01	4.08E-01	6.79E-01
165	7.69E-01	4.17E-01	7.28E-01
166	7.70E-01	4.23E-01	7.45E-01
167	7.70E-01	4.30E-01	7.68E-01
168	7.72E-01	4.38E-01	7.88E-01
169	7.74E-01	4.46E-01	8.02E-01
170	7.78E-01	4.54E-01	8.20E-01
171	7.79E-01	4.61E-01	8.30E-01
172	7.80E-01	4.68E-01	8.40E-01
173	7.81E-01	4.73E-01	8.45E-01
174	7.82E-01	4.78E-01	8.50E-01
175	7.83E-01	4.83E-01	8.53E-01
176	7.85E-01	4.89E-01	8.57E-01
177	7.88E-01	4.97E-01	8.60E-01
178	7.89E-01	5.04E-01	8.62E-01
179	7.90E-01	5.11E-01	8.64E-01
180	7.90E-01	5.19E-01	8.66E-01
181	7.91E-01	5.26E-01	8.69E-01
182	7.92E-01	5.31E-01	8.71E-01
183	7.93E-01	5.38E-01	8.73E-01
184	7.95E-01	5.44E-01	8.76E-01

TABLE 3 (Continued)

Wavelength (nm)	UV Grade Sapphire	STD Grade Sapphire	UV Grade Quartz
185	7.97E-01	5.50E-01	8.79E-01
186	7.99E-01	5.56E-01	8.81E-01
187	8.00E-01	5.62E-01	8.83E-01
188	8.00E-01	5.68E-01	8.86E-01
189	8.00E-01	5.74E-01	8.88E-01
190	8.01E-01	5.82E-01	8.90E-01
191	8.02E-01	5.87E-01	8.91E-01
192	8.04E-01	5.92E-01	8.91E-01
193	8.05E-01	5.97E-01	8.92E-01
194	8.07E-01	6.02E-01	8.92E-01
195	8.07E-01	6.07E-01	8.93E-01
196	8.07E-01	6.12E-01	8.93E-01
197	8.07E-01	6.17E-01	8.94E-01
198	8.08E-01	6.22E-01	8.94E-01
199	8.08E-01	6.27E-01	8.95E-01
200	8.08E-01	6.32E-01	8.95E-01
201	8.08E-01	6.37E-01	8.96E-01
202	8.08E-01	6.42E-01	8.97E-01
203	8.08E-01	6.47E-01	8.98E-01
204	8.08E-01	6.52E-01	8.99E-01
205	8.08E-01	6.57E-01	9.00E-01
206	8.09E-01	6.62E-01	9.01E-01
207	8.09E-01	6.67E-01	9.02E-01
208	8.09E-01	6.72E-01	9.03E-01
209	8.09E-01	6.77E-01	9.04E-01
210	8.09E-01	6.82E-01	9.04E-01
211	8.09E-01	6.85E-01	9.05E-01
212	8.09E-01	6.87E-01	9.06E-01
213	8.09E-01	6.90E-01	9.07E-01
214	8.09E-01	6.92E-01	9.07E-01
215	8.10E-01	6.95E-01	9.08E-01
216	8.10E-01	6.97E-01	9.09E-01
217	8.10E-01	7.00E-01	9.09E-01
218	8.10E-01	7.02E-01	9.10E-01
219	8.10E-01	7.05E-01	9.11E-01
220	8.10E-01	7.07E-01	9.12E-01
221	8.10E-01	7.10E-01	9.12E-01
222	8.11E-01	7.12E-01	9.13E-01
223	8.11E-01	7.15E-01	9.14E-01
224	8.11E-01	7.17E-01	9.15E-01
225	8.11E-01	7.20E-01	9.15E-01
226	8.11E-01	7.22E-01	9.15E-01
227	8.11E-01	7.25E-01	9.16E-01
228	8.11E-01	7.27E-01	9.16E-01
229	8.11E-01	7.29E-01	9.16E-01

TABLE 3 (Continued)

Wavelength (nm)	UV Grade Sapphire	STD Grade Sapphire	UV Grade Quartz
230	8.11E-01	7.31E-01	9.16E-01
231	8.12E-01	7.33E-01	9.16E-01
232	8.12E-01	7.35E-01	9.16E-01
233	8.12E-01	7.37E-01	9.17E-01
234	8.12E-01	7.39E-01	9.17E-01
235	8.12E-01	7.41E-01	9.17E-01
236	8.12E-01	7.43E-01	9.17E-01
237	8.12E-01	7.45E-01	9.17E-01
238	8.12E-01	7.47E-01	9.18E-01
239	8.13E-01	7.49E-01	9.18E-01
240	8.13E-01	7.51E-01	9.18E-01
241	8.13E-01	7.52E-01	9.18E-01
242	8.13E-01	7.54E-01	9.18E-01
243	8.13E-01	7.55E-01	9.19E-01
244	8.13E-01	7.57E-01	9.19E-01
245	8.13E-01	7.58E-01	9.19E-01
246	8.14E-01	7.60E-01	9.19E-01
247	8.14E-01	7.61E-01	9.20E-01
248	8.14E-01	7.62E-01	9.20E-01
249	8.14E-01	7.63E-01	9.20E-01
250	8.15E-01	7.65E-01	9.20E-01
251	8.15E-01	7.66E-01	9.20E-01
252	8.15E-01	7.67E-01	9.20E-01
253	8.16E-01	7.69E-01	9.20E-01
254	8.16E-01	7.70E-01	9.20E-01
255	8.16E-01	7.71E-01	9.20E-01
256	8.17E-01	7.72E-01	9.21E-01
257	8.17E-01	7.74E-01	9.21E-01
258	8.17E-01	7.75E-01	9.21E-01
259	8.17E-01	7.76E-01	9.21E-01
260	8.18E-01	7.78E-01	9.21E-01
261	8.18E-01	7.79E-01	9.21E-01
262	8.18E-01	7.80E-01	9.21E-01
263	8.19E-01	7.82E-01	9.22E-01
264	8.19E-01	7.83E-01	9.22E-01
265	8.19E-01	7.84E-01	9.22E-01
266	8.19E-01	7.85E-01	9.22E-01
267	8.20E-01	7.87E-01	9.22E-01
268	8.20E-01	7.88E-01	9.22E-01
269	8.20E-01	7.89E-01	9.22E-01
270	8.20E-01	7.90E-01	9.22E-01
271	8.20E-01	7.91E-01	9.22E-01
272	8.20E-01	7.92E-01	9.22E-01
273	8.20E-01	7.93E-01	9.22E-01
274	8.21E-01	7.94E-01	9.23E-01

TABLE 3 (Continued)

Wavelength (nm)	UV Grade Sapphire	STD Grade Sapphire	UV Grade Quartz
275	8.21E-01	7.95E-01	9.23E-01
276	8.21E-01	7.96E-01	9.23E-01
277	8.21E-01	7.97E-01	9.23E-01
278	8.21E-01	7.98E-01	9.23E-01
279	8.21E-01	7.99E-01	9.23E-01
280	8.22E-01	8.00E-01	9.23E-01
281	8.22E-01	8.01E-01	9.23E-01
282	8.22E-01	8.02E-01	9.23E-01
283	8.22E-01	8.03E-01	9.23E-01
284	8.22E-01	8.04E-01	9.23E-01
285	8.22E-01	8.05E-01	9.23E-01
286	8.22E-01	8.06E-01	9.24E-01
287	8.23E-01	8.08E-01	9.24E-01
288	8.23E-01	8.09E-01	9.24E-01
289	8.23E-01	8.10E-01	9.24E-01
290	8.23E-01	8.11E-01	9.24E-01
291	8.23E-01	8.12E-01	9.24E-01
292	8.23E-01	8.13E-01	9.24E-01
293	8.23E-01	8.14E-01	9.24E-01
294	8.23E-01	8.15E-01	9.24E-01
295	8.24E-01	8.16E-01	9.24E-01
296	8.24E-01	8.17E-01	9.24E-01
297	8.24E-01	8.18E-01	9.25E-01
298	8.24E-01	8.19E-01	9.25E-01
299	8.24E-01	8.20E-01	9.25E-01
300	8.24E-01	8.20E-01	9.25E-01
301	8.24E-01	8.20E-01	9.25E-01
302	8.24E-01	8.21E-01	9.25E-01
303	8.25E-01	8.21E-01	9.25E-01
304	8.25E-01	8.21E-01	9.25E-01
305	8.25E-01	8.21E-01	9.25E-01
306	8.25E-01	8.21E-01	9.25E-01
307	8.25E-01	8.22E-01	9.25E-01
308	8.25E-01	8.22E-01	9.25E-01
309	8.25E-01	8.22E-01	9.25E-01
310	8.25E-01	8.22E-01	9.25E-01
311	8.25E-01	8.22E-01	9.25E-01
312	8.26E-01	8.23E-01	9.26E-01
313	8.26E-01	8.23E-01	9.26E-01
314	8.26E-01	8.23E-01	9.26E-01
315	8.26E-01	8.23E-01	9.26E-01
316	8.26E-01	8.24E-01	9.26E-01
317	8.26E-01	8.24E-01	9.26E-01
318	8.26E-01	8.24E-01	9.26E-01
319	8.26E-01	8.24E-01	9.26E-01

TABLE 3 (Continued)

Wavelength (nm)	UV Grade Sapphire	STD Grade Sapphire	UV Grade Quartz
320	8.26E-01	8.24E-01	9.26E-01
321	8.26E-01	8.25E-01	9.26E-01
322	8.26E-01	8.25E-01	9.26E-01
323	8.26E-01	8.25E-01	9.26E-01
324	8.27E-01	8.25E-01	9.26E-01
325	8.27E-01	8.25E-01	9.26E-01
326	8.27E-01	8.26E-01	9.26E-01
327	8.27E-01	8.26E-01	9.26E-01
328	8.27E-01	8.26E-01	9.26E-01
329	8.27E-01	8.26E-01	9.26F-01
330	8.27E-01	8.26E-01	9.26E-01
331	8.27E-01	8.27E-01	9.26E-01
332	8.27E-01	8.27F-01	9.26E-01
333	8.27E-01	8.27E-01	9.27E-01
334	8.27E-01	8.27E-01	9.27E-01
335	8.27E-01	8.27E-01	9.27E-01
336	8.28E-01	8.28E-01	9.27E-01
337	8.28E-01	8.28E-01	9.27E-01
338	8.28E-01	8.28E-01	9.27E-01
339	8.28E-01	8.28E-01	9.27E-01
340	8.29E-01	8.29E-01	9.27E-01
341	8.29E-01	8.29E-01	9.27E-01
342	8.29E-01	8.29E-01	9.27E-01
343	8.29E-01	8.29E-01	9.27E-01
344	8.29E-01	8.29E-01	9.27E-01
345	8.30E-01	8.30E-01	9.27E-01
346	8.30E-01	8.30E-01	9.27E-01
347	8.30E-01	8.30E-01	9.27F-01
348	8.30E-01	8.30E-01	9.27E-01
349	8.30E-01	8.31E-01	9.27E-01
350	8.31E-01	8.31E-01	9.27E-01
351	8.31E-01	8.31E-01	9.27E-01
352	8.31E-01	8.31E-01	9.27E-01
353	8.31E-01	8.31E-01	9.27E-01
354	8.31E-01	8.32E-01	9.27E-01
355	8.32E-01	8.32E-01	9.27E-01
356	8.32E-01	8.32E-01	9.27E-01
357	8.32E-01	8.32E-01	9.28E-01
358	8.32E-01	8.32E-01	9.28F-01
359	8.32E-01	8.32E-01	9.28E-01

TABLE 4

REACTION RATE AND HEAT OF REACTION FOR HYDROGEN/OXYGEN/NITROGEN REACTIONS DURING PHOTOCHEMICAL IGNITION

$$k = A\,T^{-B}\exp(-C/T)$$

Reactants	Products	A	B	C	ΔH_r @ 298 K
O1D + O2	O + O2SG	5.9E-11	0.0	-67.4	-7.7
O1D + H2	H + OH	2.9E-10	0.0	0.	-43.4
O1D + N2	O + N2	3.6E-11	0.0	-121.	-45.2
O1D + O3	O2 + O2	2.7E-10	0.0	0.	-138.9
O1D + H2O	OH + OH	2.7E-10	0.0	0.	-28.4
O1D + H2O2	OH + HO2	5.0E-10	0.0	0.	-57.9
O1D + O2SG	O1D + O2	6.1E-11	0.100	4200.	7.7
O + O3	O2 + O2	1.9E-11	0.0	2300.	-93.6
O + H2	OH + H	3.7E-12	0.0	3900.	1.8
O + N2	O1D + N2	2.5E-11	0.100	22710.	45.2
O + OH	H + O2	3.8E-11	0.0	0.	-16.8
O + H2O	OH + OH	1.1E-10	0.0	9240.	16.9
O + H2O	H + HO2	6.4E-51	0.0	0.	55.3
O + HO2	OH + O2	8.0E-11	0.0	500.	-55.2
O + H2O2	OH + HO2	1.4E-12	0.0	2125.	-12.7
O + H2O2	H2O + O2	1.4E-12	0.0	2125.	-84.8
O + O + M	O2SG + M	1.7E-37	0.0	0.	-81.6
O + O + M	O2 + M	3.8E-30	1.000	170.	-119.1
O + O2 + O2	O3 + O2SG	8.2E-37	0.029	6346.	-12.1
O + O2 + O2	O3 + O2DG	1.7E-36	0.029	2191.	-2.9
O + O2 + H2O	O3 + H2O	9.9E-34	0.0	-510.	-25.4
O + O2 + M	O3 + M	1.1E-34	0.0	-510.	-25.4
O + H + M	OH + M	2.7E-30	1.000	0.	-102.3
O + OH + M	HO2 + M	1.4E-31	0.0	0.	-63.9
O2SG + M	O + O + M	1.0E-13	-0.470	40820.	81.6
O2SG + O2	O2 + O2	1.5E-16	0.0	0.	-37.5
O2SG + O3	O + O2 + O2	2.5E-11	0.0	0.	-12.1
O2SG + H2	OH + OH	7.9E-13	0.0	0.	-18.9
O2SG + N2	O2 + N2	2.0E-15	0.0	0.	-37.5
O2SG + H2O	O2 + H2O	4.7E-12	0.0	0.	-37.5

k expressed in units of s^{-1}, $cm^3 \cdot particle^{-1} \cdot s$, $cm^6 \cdot particle^{-2} \cdot s^{-1}$

ΔH_r evaluated at 298 K in units of kcal/mole

M is taken as the sum of all species present.

TABLE 4 (Continued)

Reactants			Products			$k = AT^{-B} \exp(-C/T)$			ΔHr @ 298 K
						A	B	C	
O2DG	O		O2	O		1.0E-16	0.0	0.	-22.5
O2DG	O2DG		O2SG	O2		2.0E-18	0.0	0.	-7.0
O2DG	O2		O2	O2		2.3E-20	-0.800	0.	-22.5
O2DG	O3		O	O2	O2	4.5E-11	0.0	2830.	2.9
O2DG	O3		O2	O3		3.0E-15	0.0	0.	-22.5
O2DG	H2		O2	H2		3.7E-18	0.0	0.	-22.5
O2DG	N2		O2	N2		1.4E-19	0.0	0.	-22.5
O2DG	H2O		O2	H2O		8.9E-18	0.0	0.	-22.5
O2	M		O	O	M	1.7E-02	2.430	59370.	119.1
O2	M		O2SG	M		1.0E-15	0.0	18549.	37.5
O2	M		O2DG	M		6.6E-19	0.0	11594.	22.5
O2	O2		O	O3		3.8E-12	-0.437	49407.	93.6
O2	H		OH	O		3.7E-10	0.0	8450.	16.8
O2	H2		OH	OH		1.3E-09	0.0	22500.	18.6
O2	H2		H	HO2		9.1E-11	0.0	29100.	57.1
O2	OH		O	HO2		8.4E-11	0.100	27847.	55.2
O2	OH		O3	H		2.9E-14	-0.460	38759.	76.9
O2	H2O		OH	HO2		1.2E-13	-0.500	36600.	72.1
O2	HO2		OH	O3		1.1E-14	-0.540	20269.	38.4
O2	H2O2		HO2	HO2		1.2E-13	-0.500	21068.	42.6
O2	O2	OH	HO2	O3		6.0E-39	0.118	16894.	29.8
O2	H	M	HO2	M		2.1E-32	0.0	-290.	-47.1
O3	M		O2	O	M	7.0E-10	0.0	11400.	25.4
O3	O3		O2	O2	O2	2.0E-28	0.0	0.	-68.2
O3	H		OH	O2		2.6E-11	0.0	0.	-76.3
O3	OH		HO2	O2		1.6E-12	0.0	1000.	-38.4
O3	HO2		OH	O2	O2	1.0E-13	0.0	1250.	-29.8
H	OH		H2	O1D		6.1E-11	0.110	21815.	43.4
H	OH		H2	O		1.6E-12	0.0	2960.	-1.8
H	H2O		H2	OH		1.5E-10	0.0	10250.	15.0
H	HO2		OH	OH		4.2E-10	0.0	950.	-38.5
H	HO2		H2	O2		4.2E-11	0.0	350.	-57.1
H	HO2		H2O	O		8.3E-11	0.0	500.	-55.3

k expressed in units of s^{-1}, cm^3 · particle^{-1} · s, cm^6 · particle^{-2} · s^{-1}

ΔHr evaluated at 298 K in units of kcal/mole

M is taken as the sum of all species present.

TABLE 4 (Continued)

Reactants			Products			A	B	C	ΔHr @ 298 K
						$k = AT^{-B}\exp(-C/T)$			
H	H2O2		H2O	OH		5.0E-12	-0.500	3000.	-68.0
H	H2O2		H2	HO2		2.8E-12	0.0	1900.	-14.5
H	H	H2O	H2	H2O		3.7E-30	0.500	0.	-104.2
H	H	M	H2		M	2.5E-29	0.600	0.	-104.2
H	OH	H2O	H2O	H2O		8.0E-31	0.600	0.	-119.2
H	OH	M	H2O		M	1.9E-31	0.0	0.	-119.2
H2		M	H	H		3.7E-10	0.0	48300.	104.2
H2	OH		H2O	H		3.6E-11	0.0	2590.	-15.0
H2	HO2		H2O2	H		1.2E-12	0.0	9400.	14.5
OH		M	O	H		2.3E-10	-0.210	50980.	102.3
OH	OH		O1D	H2O		5.5E-10	0.480	14357.	28.4
OH	OH		H	HO2		2.0E-11	0.0	20200.	38.5
OH	OH		H2	O2		3.3E-11	0.0	12500.	-18.6
OH	OH		O	H2O		1.0E-11	0.0	550.	-16.9
OH	H2O		H2O2	H		4.0E-10	0.0	40500.	68.0
OH	HO2		O1D	H2O2		3.7E-11	-0.075	29318.	57.9
OH	HO2		O	H2O2		8.6E-14	-0.500	10600.	12.7
OH	HO2		O2	H2O		8.3E-11	0.0	500.	-72.1
OH	H2O2		HO2	H2O		1.7E-11	0.0	910.	-29.5
OH	OH	H2O	H2O2	H2O		1.7E-33	0.0	-2550.	-51.2
OH	OH	M	H2O2		M	4.0E-34	0.0	-2550.	-51.2
H2O		M	H	OH		6.1E-32	0.0	52900.	119.2
H2O	HO2		H2O2	OH		4.7E-11	0.0	16500.	29.5
HO2	HO2		H2O2	O2		1.7E-11	0.0	500.	-42.6
HO2		M	H	O2		3.5E-09	0.0	23000.	47.1
H2O2		M	OH	OH		2.0E-07	0.0	22900.	51.2

k expressed in units of s^{-1}, $cm^3 \cdot particle^{-1} \cdot s$, $cm^6 \cdot particle^{-2} \cdot s^{-1}$

ΔHr evaluated at 298 K in units of kcal/mole

M is taken as the sum of all species present.

APPENDIX III

DISSEMINATION OF TECHNICAL INFORMATION

A. Talks and Papers

Two internal (Exxon) presentations on the program were made
to management and professionals on September 26, 1977 and May 12, 1978.
Presentations were also given at the following AFOSR Contractor's Meetings:
Air-Breathing Combustion Dynamics, West Lafayette, Indiana (Purdue
University), September 12, 1977; Unconfined Fuel-Air Explosions and
Other Combustion/Explosion Related Research, Champaign, Illinois,
November 21, 1977.

A paper entitled "Radiative Augmentation of Combustion:
Modeling" has been submitted for presentation at the meeting Eastern
States Section of the Combustion Institute on November 28, 29 and
December 1, 1978 at Miami Beach, Florida. The meeting will cover
topics in chemical and physical processes in combustion.

B. Interest Expressed by Other Scientists

The work by R. Knystautas and J. H. Lee at McGill University
on Photochemical Initiation of Detonation in Gaseous Explosive Media makes
specific use of the photochemical ignition concepts being explored by the
Exxon work. The McGill work is funded in part by AFOSR (Grant 72-2387E)
and by the National Research Council of Canada (Grants A-6819, A-3347 and
A-118). Contact and information exchange with this group has been maintained.

Contact has been made with a Mr. Raymond DeMaris of RIGS Corp.
(reactant intermediary generation systems). This group is working in the
area of photochemical combustion enhancement of sensitized reactant systems.
An August 1979 meeting is being arranged to explore mutual interest and
exchange information in this technical area.

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UNSENSITIZED IGNITION   FLAME PROPAGATION
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ULTRAVIOLET RADIATION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediary species is being investigated. Pulsed VUV (vacuum ultraviolet) light sources and continuous UV (ultraviolet) light sources are being used for this purpose. Experimental efforts are directed at elucidation of light source conversion efficiency and spectral characteristics, and reactant mixture-photon interactions. A complimentary effort involves the development of analytical capability required for modeling photochemical initiation and enhancement of combustion.

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